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ABSTRACT

The current generation of naval hydrofoils have higher speeds, superior seakeeping performance and the same payload carrying capability as naval displacement ships of the same size. This performance is the result of significant differences in areas other than the foil system. By comparing a hydrofoil and a displacement ship, differences in design criteria, standards and practices can be identified. Having identified the major differences, the displacement ship can be redesigned to hydrofoil standards. With both a hydrofoil and a displacement ship designed to the same standards, the impact of the hydrofoil's design standards on a displacement ship can be assessed, and the costs and benefits of a hydrofoil when compared to a displacement ship designed to the same standards can be evaluated.

Thesis Supervisor: Clark Graham
Title: Associate Professor of Marine Systems

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CHAPTER 1

INTRODUCTION

The technological advances of the past two decades have brought the hydrofoil from its infancy to full development as a naval combatant. The hydrofoil is the first of the class of high performance ships to reach this stage of development. The trend toward larger and slower naval combatants, which has been observed in the area of displacement ships, has been reversed by the hydrofoil. The speed capabilities of the hydrofoil place it in the class of high performance ships while its small size reverses the size trend offering with it the economies inherent with reduced size.

The objective of this analysis is to determine the design criteria and standards which have made the hydrofoil a feasible ship and to make an estimate of the characteristics of a displacement hull form of similar size with the hydrofoil's design criteria and standards. With the hydrofoil and displacement ship having the same design criteria and standards, imposing the same performance requirements in areas such as speed and endurance allows the evaluation of the positive and negative aspects of the hydrofoil and the displacement ship on an equal basis.

Classifying hydrofoils as a high performance ship requires identifying the relationships between different types of ships or vehicles. Jewel in reference 1 presented

a method of categorizing vehicles by the identification of the supporting force or sustention. This method is convenient for it characterizes all vehicles operating at the air-water interface by some combination of three forms of sustension.

Unpowered Static Lift

Powered Dynamic Lift

Powered Static Lift

This can be presented in the form of an equilateral triangle with the three forms of sustention at the vertices as shown in Figure 1. This figure provides an insight into the nature of the current generation of high performance vehicles, for they rely upon powered lift for their primary means of sustention. Hydrofoils are an example of the powered dynamic lift type vehicle and hovercraft are an example of the powered static lift type vehicle. Unpowered static lift is characteristic of large displacement type ships. However, small displacement ships such as planning craft generate dynamic lift forces at high speeds and are not solely static lift vehicles at these speeds.

For this analysis two basic types of vehicles will be examined. In the high performance ship category, the hydrofoil will be used. High performance in this context will mean a vehicle with its primary support at its operating speed provided by powered lift. Hydrofoils fall in this category as shown in Figure 1. To provide a "conventional" ship for comparison implies that it be a displacement hull

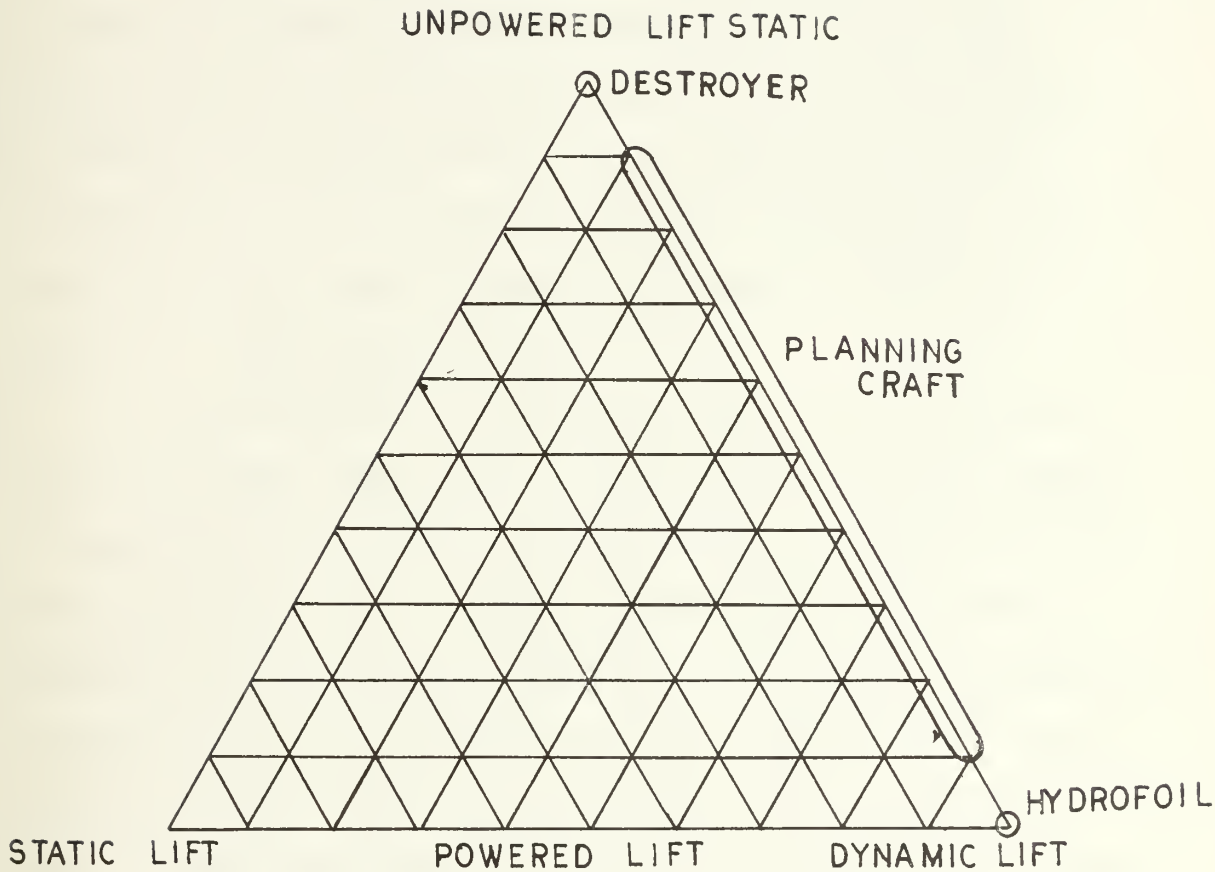

FIGURE 1 The Sustention Triangle [1]

form. However, as the size decreases and speed increases, ships with displacement hull forms have increasing sustension by powered dynamic lift as they enter the planning regime. Various types of planning craft are examples of this effect as shown in Figure 1. To ease the confusion over the relative fraction of sustention and if the vehicle should be termed high performance or not, hydrofoils will be categorized as high performance ships and other vehicles operating with a lesser fraction of powered lift will be classed as displacement ships.

The selection of the destroyer hull form for use as the displacement ship model is both traditional and based on the evaluation of the destroyer hull form by Mandel in his investigation of novelship types [2]. In Mandel's investigation, he postulated that a 2,000 ton destroyer with a machinery plant specific weight of 5 lb/SHP could attain a speed of about 65 knots. This shows the impact of a single area of improvement to hydrofoil standards demonstrating that a destroyer can compete with a hydrofoil on the basis of speed. Based on Mandel's assessment of the destroyer as the "best" of the displacement hull forms, it was chosen as the vehicle to use in the comparison. However, at high speeds and at relatively small sizes, the destroyer is surpassed in performance by the planning craft. Thus for a small ship for use in the comparison a planning craft was chosen.

CHAPTER 2

CHARACTERISTICS OF HIGH PERFORMANCE SHIPS

High performance ships have characteristics which are significantly different from a displacement ship operating at a lower speed. These characteristics are both inherent in the ship type and a result of design effort. They are major factors in the suitability of a high performance ship to fill a mission requirement, and conversely the possible range of the performance variables; speed, range, and payload carrying capacity.

The purpose of this section is to identify the areas in which there are significant differences between high performance ships and their displacement counterparts. These differences are due to the hydrodynamic aspects of the high performance vehicle, the mission requirements which it must meet, and the differences in design criteria, practices and standards which are employed to make the high performance ship feasible.

2.1 Hydrodynamic Aspects of High Speed Ships

The hydrodynamic forces which result from moving at high speed at the air-water interface have a significant effect on the viability of the ship as a useful platform. The link between hydrodynamic performance and ship impact is the required shaft horsepower for a fixed speed and displacement. A relative measure of the hydrodynamic forces and the hydrodynamic performance is the lift-drag ratio $(\frac{L}{D})$. In

estimating propulsive power requirements the lift-drag ratio provides the influence of hydrodynamic performance.

$$\frac{SHP}{\Delta} = \frac{6.87 \times V}{\eta \times \frac{L}{D}}$$

where

V = speed in knots

η = overall propulsive coefficient

L = lift or displacement

D = drag or resistance

Δ = displacement

SHP = shaft horsepower

For the same size ship at 45 knots, comparative lift-drag ratios are shown below:

Comparative Lift-Drag Ratios[20]

	Destroyer	Hydrofoil	Planning Craft
Displacement (tons)	L/D	L/D	L/D
200	---	15.0	8.8
2000	12.3	12.2	---

The relative hydrodynamic efficiency of the hydrofoil at the small displacements is apparent; however, this advantage is reversed by the time the displacement reaches 2000 tons. The

impact of the lift-drag ratio will be apparent in other areas when the effects of hydrodynamic performance on ship design requirements are examined.

The other major area of hydrodynamic performance, which is the strong point of the hydrofoil, is the seakeeping performance. From a qualitative point of view, the ability to maintain speed in a sea state reflects a good measure of this performance. The general superiority of a hydrofoil in increasing sea states is shown in Figure 2. This is the significant advantage which the hydrofoil has gained by isolating itself from environmental excitations. The cost of this isolation in terms of foil weight and volume will be examined in further detail in Chapter 3.

2.2 The Impact of Weight and Volume

For a large displacement ship operating at relatively low speeds, the impact of weight addition is either a slight reduction in speed or a slight increase in size to accommodate the extra propulsion machinery and fuel to maintain the desired speed. Whichever choice is made the effect does not jeopardize the feasibility of the platform. The effect of a weight addition on a hydrofoil can have a more significant effect. Due to the nature of the dynamic forces which provide lift, both speed and displacement are constrained to a band of operating profiles. If the increase in displacement exceeds the hydrofoil's maximum take-off weight, the ship is no longer feasible and either some payload item or

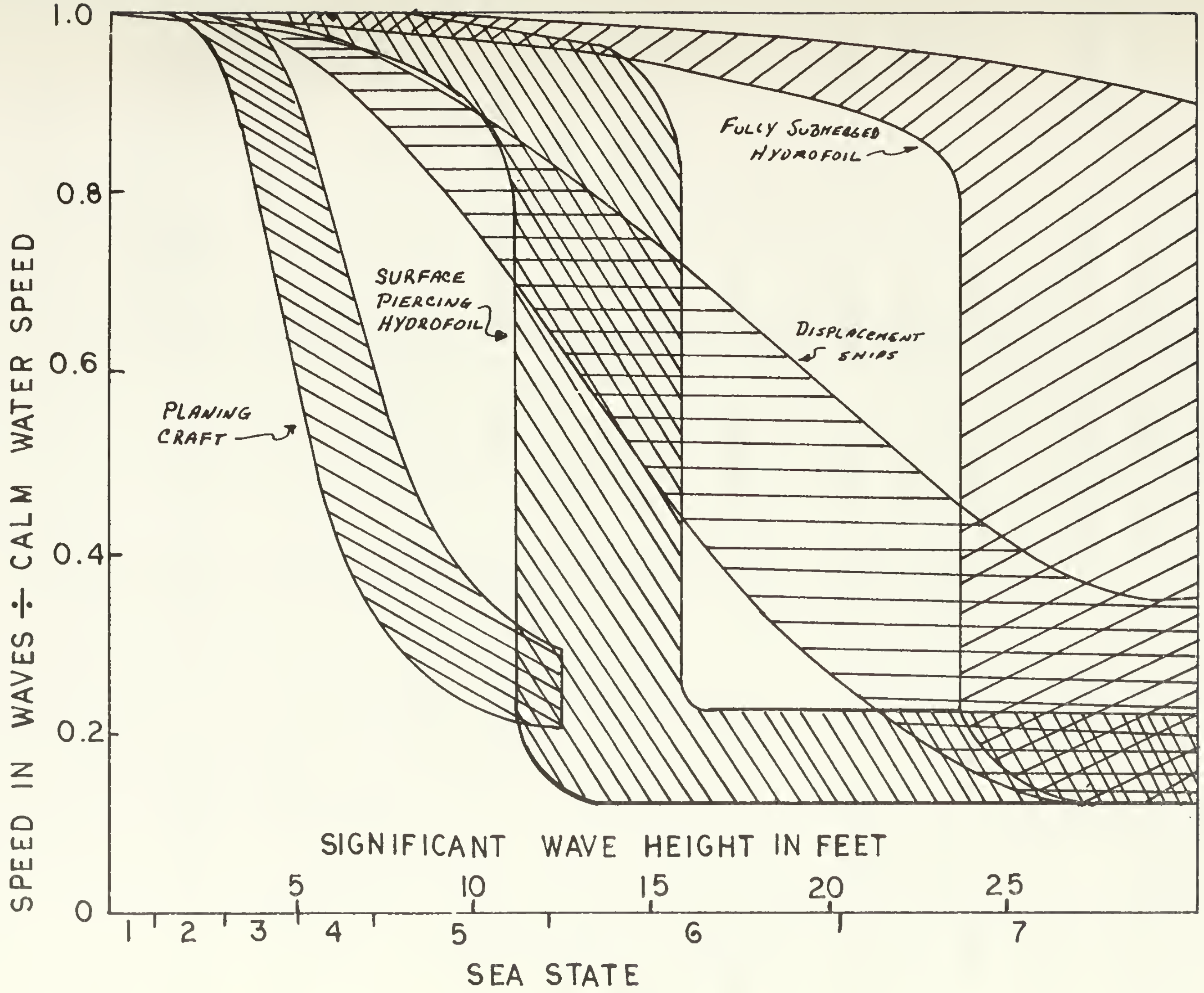

FIGURE 2 Speed Capabilities in Head Seas for Various Types of Ships [3]

fuel must be sacrificed. The alternative is an overall increase in size. Unlike the displacement ship where only the containment portion must increase to provide the necessary volume and bouyancy to support the weight addition and its effects, the hydrofoil must also increase foil size and weight to provide the support for an increase in total weight in excess of the maximum take-off weight.

Both ship types have the spiraling effect of the weight addition, resistance increase, propulsive power increase, fuel increase, and ship volume increase. The hydrofoil has the additional impact of the growing foil system and an upper limit on foil size.

The foil system represents an "overhead" which the ship must absorb in other areas if it is to be a useful platform. The weight of the foil system is significant and its impact increases with size as predicted by Hoerner [4] and reflected in recent hydrofoil designs as shown in Figure 3.[1] The overhead increases with increasing displacement and foil size grows until the feasibility limits for foil size are reached. As a result hydrofoils are highly integrated designs where weight and space are at a premium. The design,

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[1]Hoerner's prediction of foil weight as a fraction of full load displacement is

$$\frac{W_f}{W} = 6.5 + 1.3 \times 10^{-2} \quad W^{1/3}$$

Where W_f is foil weight
and W is full load displacement.

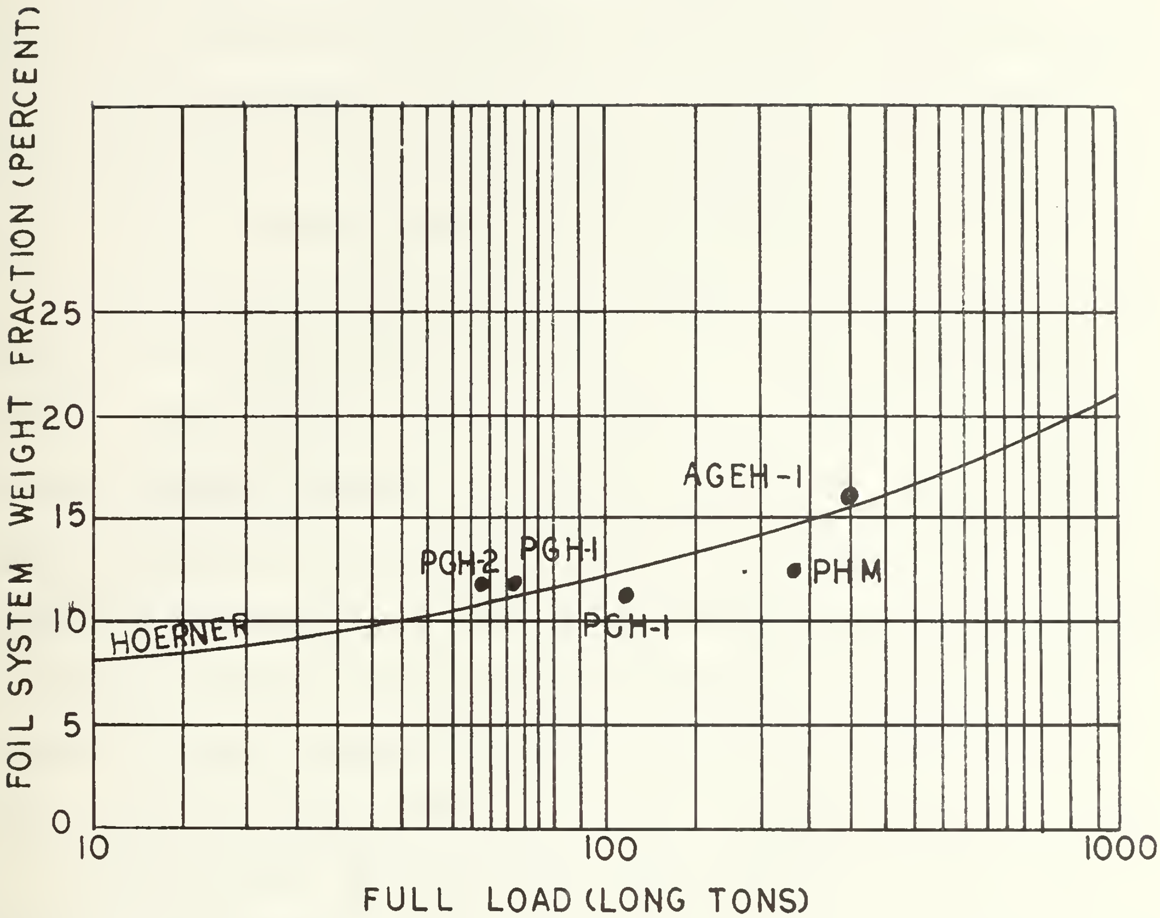

FIGURE 3 Weight Trend for Hydrofoil Lift Systems [5]

as a result of this high degree of integration, does not evolve but rather bursts into existance when the platform becomes feasible and integrated in all aspects of the design. To be able to absorb the overhead which the foils have imposed, hydrofoils have relied heavily upon the application of technology somewhat foreign to displacement ship design. The technology and the weight consciousness is more akin to the aircraft industry than the marine industry.

The impact of weight consciousness is significant if one looks at the relationship between foil weight and payload weight. For a wide range of displacement ships the average payload weight fraction is about 12 percent.[2] By contrast the average foil system weight is in that range also. A hydrofoil designed by conventional displacement ship standards would have little if any payload carrying capability. The result of weight consciousness is that the hydrofoil also has a payload weight fraction of about 12 percent.

The advances in lightweight structures are one major area of improvement. The impact of aluminum structures is shown in Figure 4. Structural weight fraction and structural density both show the impact of lightweight hull structures.

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[2]Payload is defined as weight groups 4 and 7, Amunition, Aircraft and Aircraft related fuel and stores. The payload weight fraction is the ratio of payload weight to full load displacement.

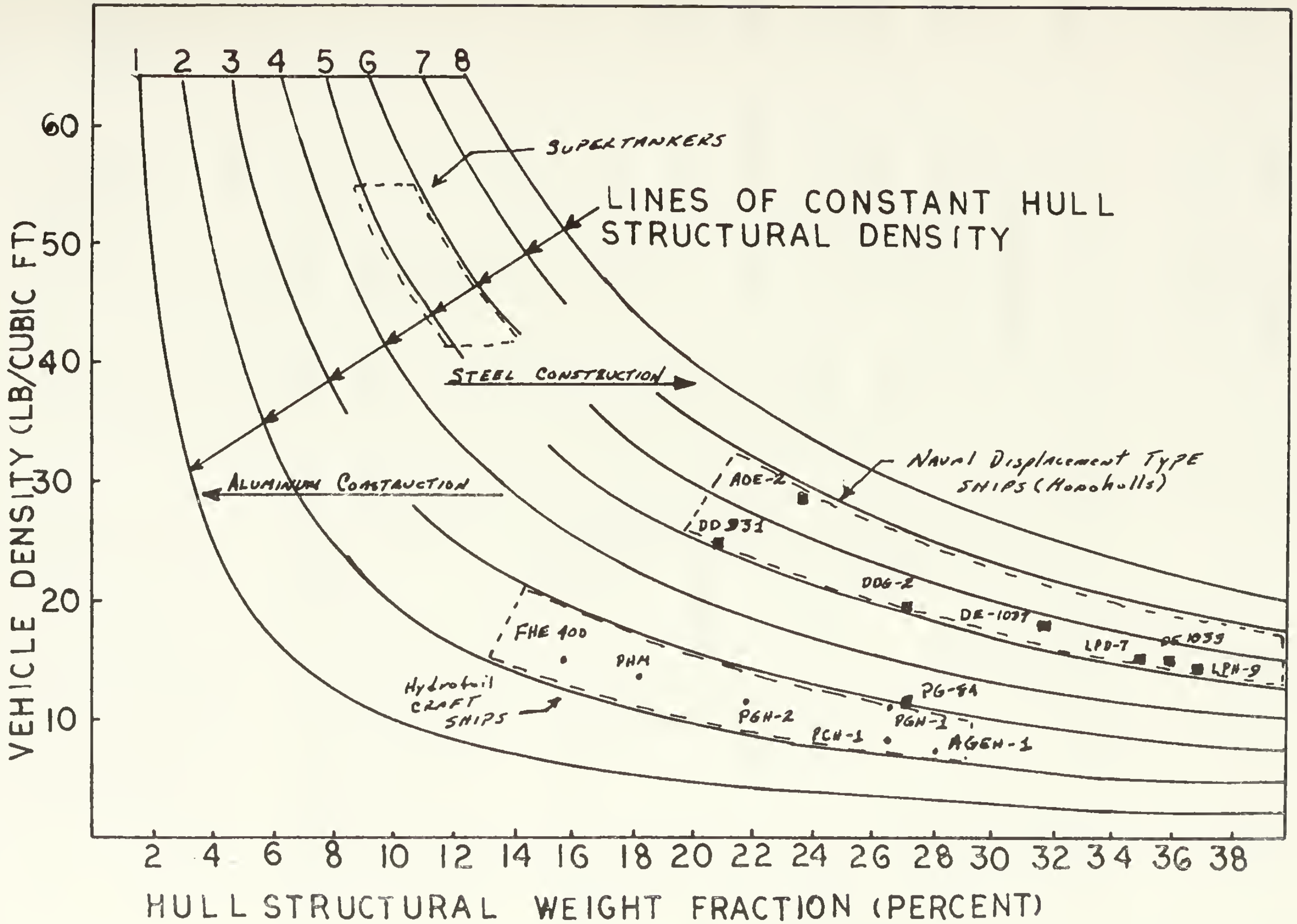

FIGURE 4 Ship Structural Weight Relationships [5]

	Structural Weight Fraction	Structural Density
Hydrofoil Ships (Aluminum Hull Structures)	~20%	2-3 lb/ft^3
Naval Displacement Type Ships (Steel Hull Structures)	~30%	5-7 lb/ft^3

The differences are not restricted only to small ships. Structural estimates for a variety of ships indicate that an aluminum hull structure is on the average 55 percent of the weight of a steel hull structure [6].[3] The use of aluminum as a hull structural material is not without its complications. It has a definite fatigue life and also requires specific measures to protect it from the effects of fire. The advantages are significant and the payload carrying capacity of hydrofoils would be severely limited if aluminum structures were not feasible.

Speed, hydrodyanmic efficiency (lift-drag ratio) and power plant size and weight are all closely related. The relationship between power requirements and speed reflects the hydrodynamic influences,

$$\frac{SHP}{\Delta} \sim \frac{V}{\eta \frac{L}{D}}$$

[3]An aluminum hull structure for DDG-2 (Figure 4) would result in a structural density of 3.5 lb/ft^3 and a structural weight fraction of 15.6 percent.

and the relationship between propulsion plant specific weight and machinery weight fraction reflect the influence of the power plant type.

$$\frac{Wm}{\Delta} \sim \left(\frac{SHP}{\Delta}\right) (\omega m)$$

where

SHP = required shaft horsepower

Δ = displacement

V = speed

L = lift

D = drag or resistance

η = propulsive efficiency

Wm = machinery plant weight

ωm = propulsion plant specific weight = $\dfrac{\text{propulsion plant weight}}{\text{installed shaft horsepower}}$

therefore

$$\frac{Wm}{\Delta} \sim \frac{V \ \omega m}{\eta \ \frac{L}{D}}$$

As Mandel observed the gains in speed have been due to the reduction in specific machinery weight rather than improvements in the lift to drag ratio [2]. The inference is that to keep the ratio of machinery weight to displacement within bounds the specific machinery weight must decrease with increasing speed and rapidly decreasing lift-drag ratio.

An indication of this effect is shown in Figure 5 for a range of effective lift-drag ratios and speeds of 45 and 30 knots. Restricting the available weight fraction for machinery establishes the limits for the specific machinery weight. Conversely the range of available machinery plants sets the limits on the machinery weight fraction. Examining the specific machinery weight of conventional prime movers for both displacement ships and hydrofoils shows the impact of the high horsepower density of the current generation hydrofoils.

Power Plant Type	Specific Machinery Weight	Machinery Weight $\eta L/D=10$	Fraction for V = 45 kts. $\eta L/D = 5$
Steam (Destroyer) [7]	26 lb/SHP	0.355	0.71
Gas Turbine (Destroyer) [7]	15 lb/SHP	0.21	0.42
Gas Turbine (Hydrofoil)	5 lb/SHP	0.07	0.14

The impact of the power plant specific weight in the small ship range ($\eta\frac{L}{D}=5$) shows the necessity for lightweight power plants. Along with the increase in the power to weight ratio is an accompanying reduction in volume.

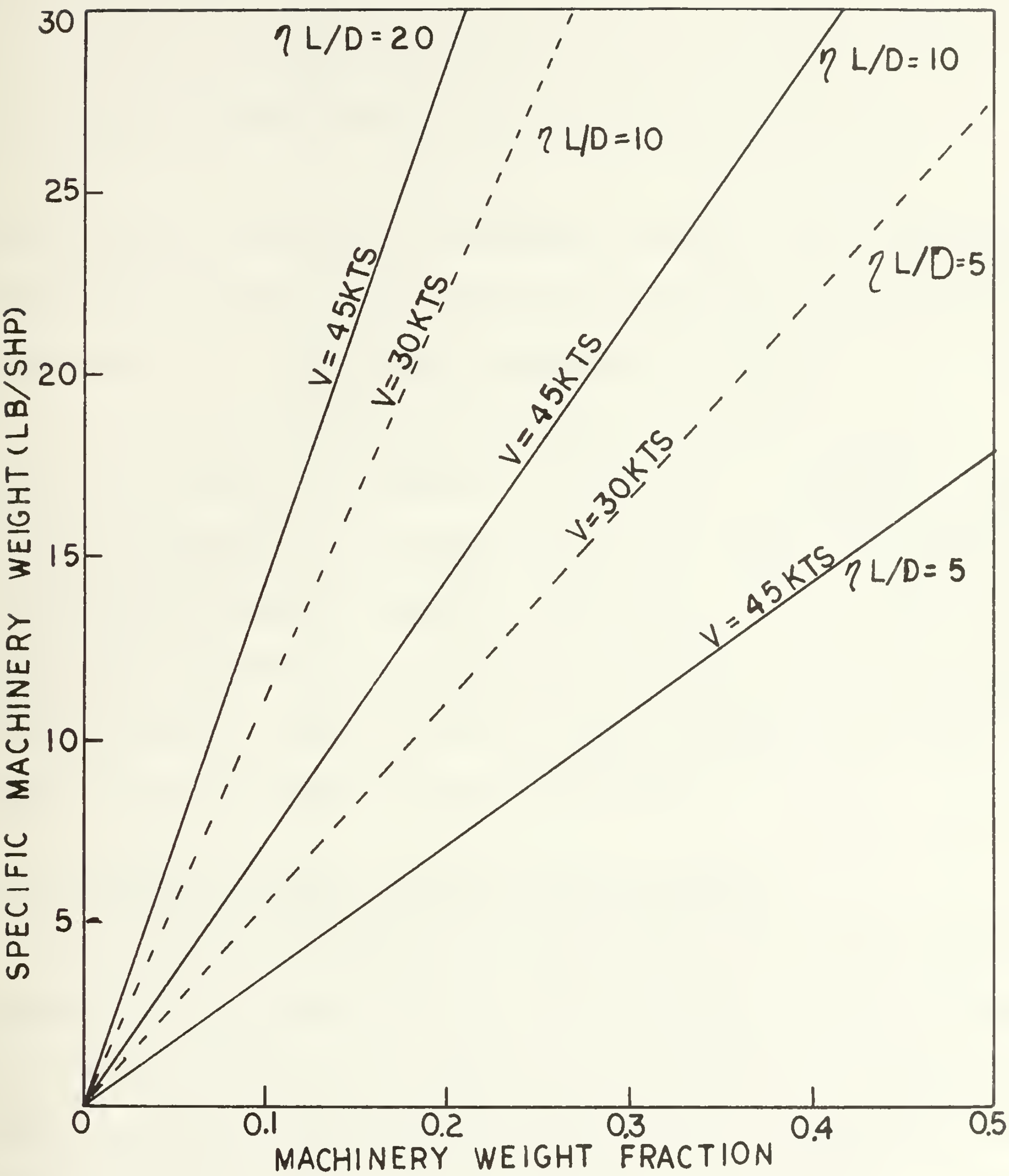

FIGURE 5 Machinery Weight Fraction Relationship to Propulsion Plant Specific Weight

	ft^3/SHP
Steam (Destroyer) [7]	2.5
Gas Turbine (Destroyer) [7]	1.5
Gas Turbine (Hydrofoil)	0.75

Since volume represents containment weight, hull structure, auxillary systems, and outfit and furnishings, the reduction in volume is in fact also a reduction in weight.

The impact of volume is apparent not only in the machinery area but throughout the ship for hydrofoils. The weight to support a cubic foot of volume based on current hydrofoil standards is about 4.3 pounds.[4] This is the penalty for enclosing in structure and providing outfitting and services to a cubic foot of unused volume. Thus the emphasis is on volume as well as weight.

2.3 Hydrofoil Design Criteria and Standards

The hydrofoil designer's motivation for weight consciousness was discussed in the previous section and the impact of weight in some major areas was investigated. However, there are some areas where an effort to save weight or volume may be quite subtle or have an unanticipated impact. Several of these areas are intact and damage stability; system redundancy; reliability, maintainability and availability; habitability; operating profile and margins.

[4]Based on current hydrofoil standards of 2.5 lb/ft^3 for hull structure, 0.94 lb/ft^3 for auxillary systems and, 0.86 lb/ft^3 for outfit and furnishings.

Damage and intact stability are an area in which the designer may be tempted to encroach in an effort to save weight. In the current designs this has not occurred for the same stability standards apply equally to hydrofoils and displacement ships. In the same manner the customary redundancy in areas such as power generation; propulsion systems and other systems affecting mobility have not been compromised to save weight.

The requirements for reliability, maintainability, and availability are much harder to assess. The operating profile and the ship's maintenance concept all impact these areas. The complexity of the foil system must be acknowledged as a factor in the overall availability of the ship. The trend to make the ship compact as a whole indicates that access and thus, in some degree, maintainability has to be compromised.

The area of habitability offers one of the best inroads to the reduction of volume and weight. Hydrofoils are by current standards austere but reflect habitability standards which are by no means unacceptable. The hydrofoil designer has in this area attempted to do more with less.

The general area of margins has hidden within it many pitfalls. Margins in weight, propulsion power, accommodations, and generator capacity can have a significant impact on the design particularly in a small ship. The impact of the shaft horsepower on the installed power plant and fuel

storage capacity is significant. The variation in shaft horsepower margin by ship type, although in some cases apparently small, can be significant. The values presented by Wilson and Lombardi [8] were used in this analysis in an effort to be consistent with current practice. Margins in other areas were not addressed since for comparative purposes ships were redesigned to a common set of standards and criteria at the level of detail investigated.

CHAPTER 3

A COMPARATIVE ANALYSIS OF NAVAL HYDROFOILS AND DISPLACEMENT SHIPS

The differences in design and construction between hydrofoils and displacement ships in areas other than the means of sustension prevent a logical comparison of the advantages and disadvantages inherent in these ship types. To allow a comparison to be made, the differences in the ships are analyzed as they are presently constructed and the differences in design criteria and standards are reduced to allow a side-by-side comparison.

The rationale for the ships selected for the study is contained in Section 3.1, followed by the method of analysis and computer model in Sections 3.2 and 3.3 respectively. The comparative analysis of a small hydrofoil and a similar size planning craft is contained in Section 3.4. A similar analysis for a large hydrofoil and a displacement ship is contained in Section 3.5.

3.1 Selection of Ships

The desire to examine on an equal basis a hydrofoil and its non-hydrofoil counterpart directly affected the ships available for the study. The first criteria was that the ships should be designed as combatants as opposed to test beds for research and development purposes. This limited the hydrofoil population significantly. This restriction had two effects. The first was the imposition of the same

warfare related standards required of a naval combatant to the hydrofoil. The second was the elimination of a wide diversity in apparent design criteria which appeared in the examination of the hydrofoils whose initial purpose had been as a proving ground for the technology.

Having limited the available number of hydrofoils significantly, it was determined that a side-by-side comparison of a hydrofoil and its displacement counterpart would yield the most useful information. The hydrofoil designs selected were then chosen for their diversity in size, performance, and mission capabilities.

At the small ship end of the spectrum, the 230 ton NATO HYDROFOIL (PHM), a joint U.S.-NATO project, was chosen. It is a small, single mission area, gas turbine powered ship with a small crew and limited endurance. For a larger ship, the Deepwater Escort Hydrofoil (DEH), a product of design studies by the Boeing Corporation and the U.S. Navy was used. A 1200 ton multimission ship with an endurance sufficient for ocean crossings, it represents the conceptual design of a large hydrofoil.

Having selected the hydrofoils to be examined, the candidates for a displacement ship to use as a yardstick for comparison were examined. To attempt to provide a one-to-one comparison of the current state-of-the-art in displacement ship design with hydrofoil design the following selection criteria were used:

·Similar Size

·Similar Mission Area Capabilities

·Recent Design

Based on these criteria the PG-84 class of patrol boats was selected for comparison with the PHM. A 240 ton hard-chine planning hull capable of calm water speeds of 40 knots, it provided a close match to PHM in both size and speed. It has the same mission capability as PHM and a similar endurance. Built in the period 1966 to 1970, the ships were the first U.S. Naval combatants with gas turbine propulsion and aluminum hull construction. Other than a 10 year difference in technology, the ships are very similar

Selection of the counterpart for the DEH was not as straightforward. There are no recent designs in the 1200 ton range by the U.S. Navy. The result was the selection of a current design with a gas turbine propulsion plant for the comparison of current displacement ship design standards and criteria with those of DEH. To provide a side-by-side comparison, a 1200 ton high speed displacement ship was developed from a standard series estimate and PG-84 design standards.

The smallest current gas turbine design, other than PG-84, is the new Patrol Frigate Class (FFG-7).[5] A current

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[5]The Patrol Frigate Class was originally designated the PF-109 class but was subsequently changed to the FFG-7 class.

design with multimission capabilities, it displaces approximately 3500 tons. It has a large crew by hydrofoil standards, three times the size of DEH, and a maximum speed of about 28 knots. The differences in size and speed led to the selection of a 1200 ton series 64 hull form for the side-by-side comparison. This disparity in size and performance for the same general mission capability provides a very visible indication of the impact of hydrofoil technology. The principle characteristics of PHM, PG-84, DEH and FFG-7 are presented in Table 1.

The choice of ships permits not only a basis for evaluating the features which are characteristic of a range of ship sizes. It also provides the basis for assessing the impact of gaining the hydrofoil's superior speed both in calm water and in a sea state.

3.2 Method of Analysis

To provide a basis for evaluating those areas in which there is an apparent difference in the standards, criteria or design philosophy between a hydrofoil and its displacement counterpart, an analysis of the weight and volume utilization of the two ship types was made. As a derivative of the weight and volume analysis, a collection of specific parameters was developed. The specific parameters are ratios of weight, volume or other characteristics such as crew size or shaft horsepower which give a quantitative measure of the ship's characteristics and design criteria.

TABLE 1

SHIP'S CHARACTERISTICS

	PG-84 (19)	PHM(19)
Displacement (tons)	245	230
Length (ft)	164.5	130
Beam (ft)	23.8	29
Draft (ft)	9.5	9.5
Main Engines	2 Diesel/1 GT CODAG	2 Diesel/1 GT CODAG
Propulsor	Propeller	Waterjet
Speed (kts)	40+	40+
Range (N.M.)		600+
Complement	24	21
Payload	3"/50 Cal Gun Standard Missile or 40MM Gun MK87WCS	76MM OTTO Melara Gun Harpoon Missile MK92FCS

TABLE 1 (continued)

SHIP'S CHARACTERISTICS

	DEH (15)	FFG-7 (19)
Displacement (tons)	1200	3450
Length (ft)	200	445
Beam (ft)	40	45
Draft (ft)	36	24.5
Main Engines	2 GT/2 GT COGOG	2 GT
Propulsor	Propeller	Propeller
Speed (kts)	40+	28+
Range (nim)	~2600 at 40+ kts	4500 at 20 kts
Complement	82	185
Payload	Missile Launcher Torpedo Tubes 76MM OTTO Melara Gun Towed Sonar, Foil Mounted Sonar MK92FCS 20MM CIWS	1-76MM OTTO Melara Gun 1-Tartar Missile Launcher 2-SH2D Lamps Helo 2-Triple Torpedo Tubes 1-20MM CIWS SQS-56 Sonar MK92FCS

The specific parameters provide a better indication of the magnitude of the difference in a selected area than weight or volume alone. They also provide the input for conceptually upgrading the displacement hull to hydrofoil design standards.

The weight analysis was based on the weight groupings of the Ship Work Breakdown Structure System Classification [9]. The weight groups and their definitions as used in this analysis are contained in Table 2. Payload weight was used as the figure of merit in evaluating the respective platforms. The definition of payload is therefore significant if consistent conclusions are to be drawn. For hydrofoils and other high performance ships, such as surface effect ships and air cushion vehicles, payload is often defined as the variable load (fuel, personnel, stores, water, ammunition and aircraft), Armament (Weight Group 7) and Command and Surveilance (Weight Group 4). This may be a valid concept when comparing similar high performance vehicles. However, when comparing these high performance ships with ships outside that category, a more restrictive definition of payload gives a better indication of the platforms capability. Payload in the context to be used in this analysis is the portion of the ship's displacement attributable to its primary military mission, excluding mobility factors. This is normally used in the evaluation of displacement ships and is defined as the weight groups for command and surveillance (Weight Group 4) and armament (Weight Group 7), and those items in the variable load directly related to the military

TABLE 2

WEIGHT CLASSIFICATIONS [9]

Group 1	Hull Structure Framing, Shell Plating, Bulkheads, Decks, Deck House Structure, Masts, Foundations
Group 2	Propulsion Plant Prime Movers, Transmission Systems, Propulsors, Propulsion Support Systems (Fuel Oil & Lube Oil)
Group 3	Electric Plant Power Generation Systems, Power Distribution Systems, Lighting System, Power Generation Support Systems
Group 4	Command and Surveilance Command & Control Systems, Navigation Systems, Exterior Communications, Surface & Subsurface Sensors, Countermeasures, Fire Control Systems
Group 5	Auxiliary Systems Heating, Ventilation & Air Conditioning Systems, Seawater Systems, Freshwater Systems, Anchor, Mooring & Boat Handing Systems, Foil Systems & Controls
Group 6	Outfit and Furnishings Non-Structural Compartmentation, Painting, Insulation, Deck Covering, Messing, Berthing & Sanitary Facilities, Furnishings and Fixtures, Commisary Equipment, Office Furnishings, Storeroom Fixtures
Group 7	Armament Gun Systems, Missile Launching Systems, Torpedo Launching Systems, Ammunition Stowage and Handling Systems
Loads	Personnel - Crew and Crew's Effects Stores - Fresh, Frozen and Dry Foodstuffs General Stores - Fuel Oil - For Main Propulsion, Power Generation Lubricating Oil - Potable Water - Ammunition - For Ship's Weapons

TABLE 2 (continued)

Aircraft - Aircraft Weight Only

Aviation Stores - Repair Parts and Tools for
Aircraft Maintenance

Aviation Fuel -

mission; ammunition, aircraft, and aircraft related stores and fuel. The impact of this definition will not be overly apparent in the data presented since the items excluded from the high performance ship definition are derived from the same set of requirements for the side-by-side comparison. The variation in these components of the variable load is a reflection of the platform's characteristics in response to the requirement. An excellent example of this is fuel weight. With displacement, speed, range and prime mover fixed, the fuel weight is a direct reflection of the platform's hydrodynamic efficiency. For a side-by-side comparison with equivalency in as many areas as possible, payload weight is a good quantitative measure of the platform's merit.

Since the scope of the designs examined ranged from completed ships with returned weight statements (PG-84) to feasibility studies (DEH), the margin provided in the weight statements varied significantly. To place all the designs on a similar basis, the weight margin was distributed equally among the seven major weight groups.

A volume analysis was conducted to assess the volumetric impact of hydrofoil technology. The volume categories presented in Table 3 are derived from the proposed Navy Space Classification System [10] and give an indication of the major functions requiring an allocation of space. Volume fractions were used as an indication of a ship impact in areas where there was no corresponding weight impact. This occurs in the areas of access, voids, storerooms and other

TABLE 3

VOLUME CLASSIFICATION [10]

Military Mission Performance (Payload Volume)

- Communications Detection and Evaluation Spaces
- Weapons Systems Spaces
- Aviation Spaces
- Ship Control

Ship's Personnel (Personnel Volume)

- Living Spaces - Berthing, Messing, and Sanitary
- Supporting Functions - Administrative, Food Preparation, Medical and Personnel Services
- Stowage - Stores and Provisions Storerooms and Potable Water Tankage

Ship Operation

- Main Propulsion Machinery Spaces - (Machinery Box Volume)
    - Main Propulsion Machinery and Auxiliaries, Electrical Power Generators
- Auxiliary Systems and Equipment - External to the Machinery Box (Auxiliary Systems Volume)
    - Steering Systems, Ventilation Systems, Deck Auxiliaries
- Stowage
    - Endurance Fuel Oil (Fuel Volume)
    - Stores and Supplies (Stores Volume)
- Tankage
    - Ballast Tanks, Voids
- Passageways and Access (Access Volume)

service type spaces such as steering gear rooms, fan rooms, and deck machinery spaces.

To provide an indication of relative performance in a selected area, a set of specific parameters was developed. These parameters serve a twofold purpose. They are a more directly applicable quantitative measure of performance than weight, volume, weight fraction or volume fraction. They provide the basis for changing the design standards and criteria in a conceptual redesign. The selection of the parameters was in many cases based on the weight estimating correlations from Section 6 of Weight Control of Naval Ships, Volume 1 [11]. The selection of the volume parameters was based on a logical correlation between the volume requirement and the prime utilization of the space. The parameters selected and the definition of the parameters and terms used are contained in Table 4.

3.3 Computer Model

The computer model was developed to permit an investigation of the impact of hydrofoil design criteria and standards on a displacement hull form and to give an indication of the sensitivity of the figure of merit to the variation in design criteria and standards. The model was developed to be a tool to provide comparisons between ships with known parameters such as size, speed, shaft horsepower, and crew size. Therefore, it is not a synthesis model and does not check for feasibility in areas other than weight and volume.

TABLE 4

SPECIFIC PARAMETERS

Parameter	Definition	Units
Vehicle Density	Full Load Weight/Total Enclosed Volume	lb/ft^3
Structural Density	Hull Structural Weight (GP1)/ Total Enclosed Volume	lb/ft^3
Propulsion Plant Specific Weight	Propulsion Plant Weight (GP2)/ Propulsion Shaft Horsepower	lb/SHP
Specific Machinery Volume	Machinery Box Volume/Installed Propulsion Horsepower	ft^3/SHP
Payload Density	Payload Weight/Payload Volume	lb/ft^3
Electrical System Specific Weight	Electrical Plant Weight (GP-3)/ Installed KW of Generator Capacity	lb/KW
Specific Personnel Volume	Total Personnel Volume/Crew Size	ft^3/MAN
Arrangement Volume Fraction	Arrangement Volume/Total Enclosed Volume	--
Auxiliary Systems Volume Fraction	Auxiliary System Volume/Total Enclosed Volume	--
Stores Volume Fraction	Stores Volume/Total Enclosed Volume	--
Outfit & Furnishing Density	Outfit & Furnishing Weight (GP-6)/ Total Enclosed Volume	lb/ft^3
Auxiliary System Density	Auxiliary System Weight (GP-5)/ Total Enclosed Volume	lb/ft^3

3.3.1 Objective of the Computer Model

The objective of the computer model was to reduce the differences in design criteria and standards that exist between hydrofoils and displacement ships. The intent was to enable a comparison of ships with similar characteristics in all areas except the hull type.

Since the sensitivity of the hydrofoil to design changes prohibited the redesign of the hydrofoil down to displacement ship standards. The more logical alternative of designing the displacement ship up to hydrofoil standards was undertaken. With this approach the impact of the hydrofoil's design criteria would be reflected in a change in the figure of merit.

A secondary objective of the computer model was to test the sensitivity of the figure of merit to changes in the design parameters both individually and collectively. This provides an indication of the relative importance of the design parameters. It also provides an indication of the range of parameters for which the conclusions are valid.

3.3.2 Description of the Computer Model

The model was designed for analysis rather than synthesis. It therefore utilizes a fixed ship size and type and balances weight and volume to produce a balanced ship in these two areas. The model is an itterative series of weight and volume calculations based on a fixed displacement. The input to the model is the performance parameters of the

hydrofoil with which the comparison is to be made. These are maximum speed in calm water, range at maximum speed in calm water, crew size, stores endurance period, and installed electrical generation capacity. After providing the weight and volume necessary to support the functions required to meet these performance requirements, the difference between the weight utilized and the initial displacement is payload, the figure of merit. The sizing of the weights and volumes is based on the specific parameters from the analysis of the hydrofoil used in the comparison. This results in the upgrading of the displacement hull's standards.

The significant difference between the hull forms other than the foil system is the speed-power relationship. Since the displacement and speed are known, the required shaft horsepower for the maximum speed is also known from a characteristic speed-power curve for the displacement hull form. This is used as an input to the program. The characteristics of the prime mover also have an impact on the model. For the hydrofoils involved, the prime mover was the General Electric LM2500. The assumption was made that the upgraded displacement ship would have the same prime mover and thus the same specific fuel comsumption rate characteristics.

3.3.2.1 Weight Algorithm

The weight algorithm balances the specified displacement with the categories of weight utilization other than payload. The weight which remains after all the

containment, mobility, personnel and other miscellaneous weight demands are met is the weight available for payload.

The weight algorithm has three sections which are effectively independent of each other relying solely on the performance parameters and specific parameters for the respective area. The weights associated with containment, Group 1 (Hull Weight), Group 5 (Auxiliary Weight) and Group 6 (Outfit and Furnishings) are the only groups which are volume dependent and as such are affected by the volume algorithm. The prediction of these three weight groups is based on an assumed volume and the respective specific parameter for the weight group. For the initial itteration, the volume is estimated from the displacement and vehicle density. On later itterations it is estimated from the volume algorithm.

The propulsion machinery weight, Group 2, and Fuel Weight are computed from the inputs of required shaft-horsepower at maximum speed, shaft horsepower margin, the maximum speed, and the range at the maximum speed. Closely associated with these weights is the electrical system weight, Group 3, and the required fuel for its prime movers. The propulsion machinery weight is estimated from the propulsion machinery specific density (lb/SHP). Similarly the electrical system weight is estimated from its specific density (lb/KW). The fuel weight, however, is a function of several variables, shaft horsepower, range, speed, electrical plant size, and specific fuel consumption rates. The weight

of fuel is estimated in two parts. The fuel weight for the electrical plant is estimated from the installed electrical generator capacity, the prime mover's assumed specific fuel consumption rate, and the estimated length of operation based on time at full speed.[6]

$$W_f = [\frac{KW}{EFF} \times 1.34 \frac{HP}{KW} \times SFCA \times (\frac{R}{V})]/2240$$

where

W_f = electrical plant fuel weight

SFCA = electric plant prime mover specific fuel consumption rate

KW = installed generator capacity

EFF = assumed generator efficiency

R = range at maximum speed

V = maximum speed

The fuel estimate is conservative since it is based on installed generator capacity rather than the actual electrical loads.

The propulsion plant fuel weight is predicted in a slightly different manner. In ships which have relatively

[6]Although this is the "best case" for the electric plant fuel, it is the worst case for the total fuel load. The electric plant fuel load would be a greater fraction of the total fuel load at a lower speed, e.g., the hullborne endurance speed for a hydrofoil. Due to the large fuel fraction required for the high speed endurance, the available hullborne endurance normally exceeds the required endurance even with the longer period of generator operation.

large fuel fractions the Brequet range equation is used. It accounts for the reduction in displacement and attendant reduction in required shaft horsepower as fuel is consumed. This reduction is presented as an increase in range since a lower power requirement also implies a lower rate of fuel consumption. The Brequet range equation reflects these facts.

$$RB = \frac{2240}{SFC} \left(\frac{\Delta V}{SHP}\right) \ln \left(\frac{\Delta}{\Delta - W_f}\right)$$

Where

RB	=	Brequet Range
SFC	=	Propulsion Prime Mover Specific Fuel Consumption Rate
Δ	=	Displacement Full Load
V	=	Maximum Speed
SHP	=	Required Shaft Horsepower at Maximum Speed With SHP Margin
W_f	=	Propulsion Fuel Weight

The difference between the range predicted by the Brequet equation and the standard range prediction without accounting for fuel burnoff is significant. As shown in Figure 6, at a fuel fraction of 25% the Brequet range is 15% greater. This has a definite effect on the predictions of the model. The total fuel weight is then the sum of the propulsion and electrical plant fuel weights with an appropriate tailpipe allowance.

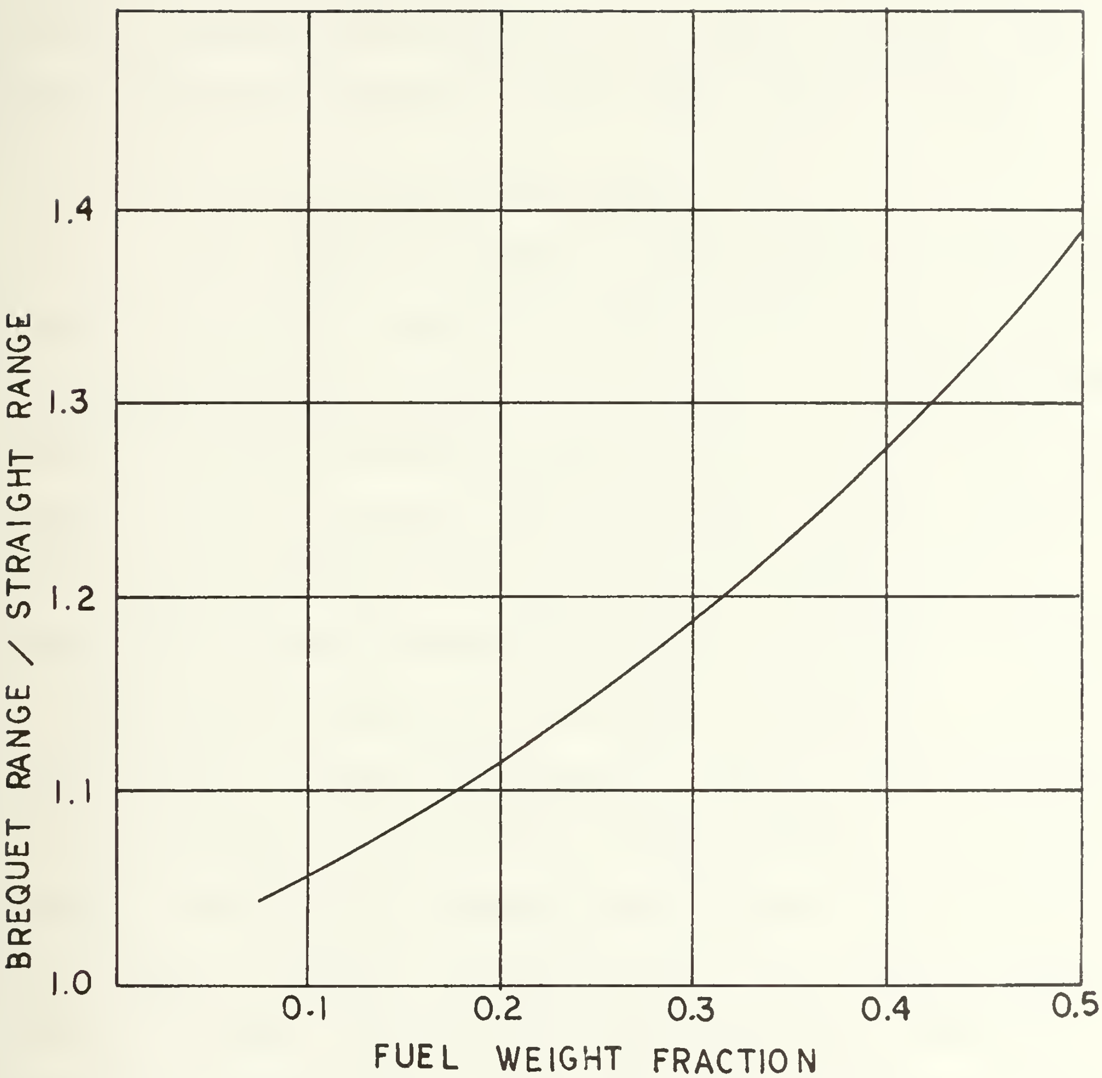

FIGURE 6 Brequet Range Correction Based on Fuel Fraction

The weight of the crew and stores are again determined by the specific ratios based on crew size and the stores endurance period. The difference between the estimated weights in the areas of containment, mobility and personnel and the assumed displacement is the payload weight. The weight algorith is shown in flow chart form in Figure 7.

3.3.2.2 Volume Algorithm

The volume algorithm is very similar to the weight algorithm since it requires a volume balance between assumed volume and required volume. An initial input to the weight algorithm is an estimated volume based on the required displacement and an assumed vehicle density. Since portions of the weight estimate are based on the volume estimate, there is a coupling between the weight and volume algorithms.

The volume algorithm allocates the estimated volume to the respective volume requirements. Some volume requirements are based solely on a required volume fraction. Arrangements volume, stores value, and auxiliary volume are determined in this manner. However, machinery box volume, fuel volume and personnel volume are based on their respective specific parameters. The difference between the estimated volume and the volume utilized by these functions is the volume available for payload. To ensure a sufficient volume is available to contain the payload a required payload density range is specified. If the payload density falls outside the range,

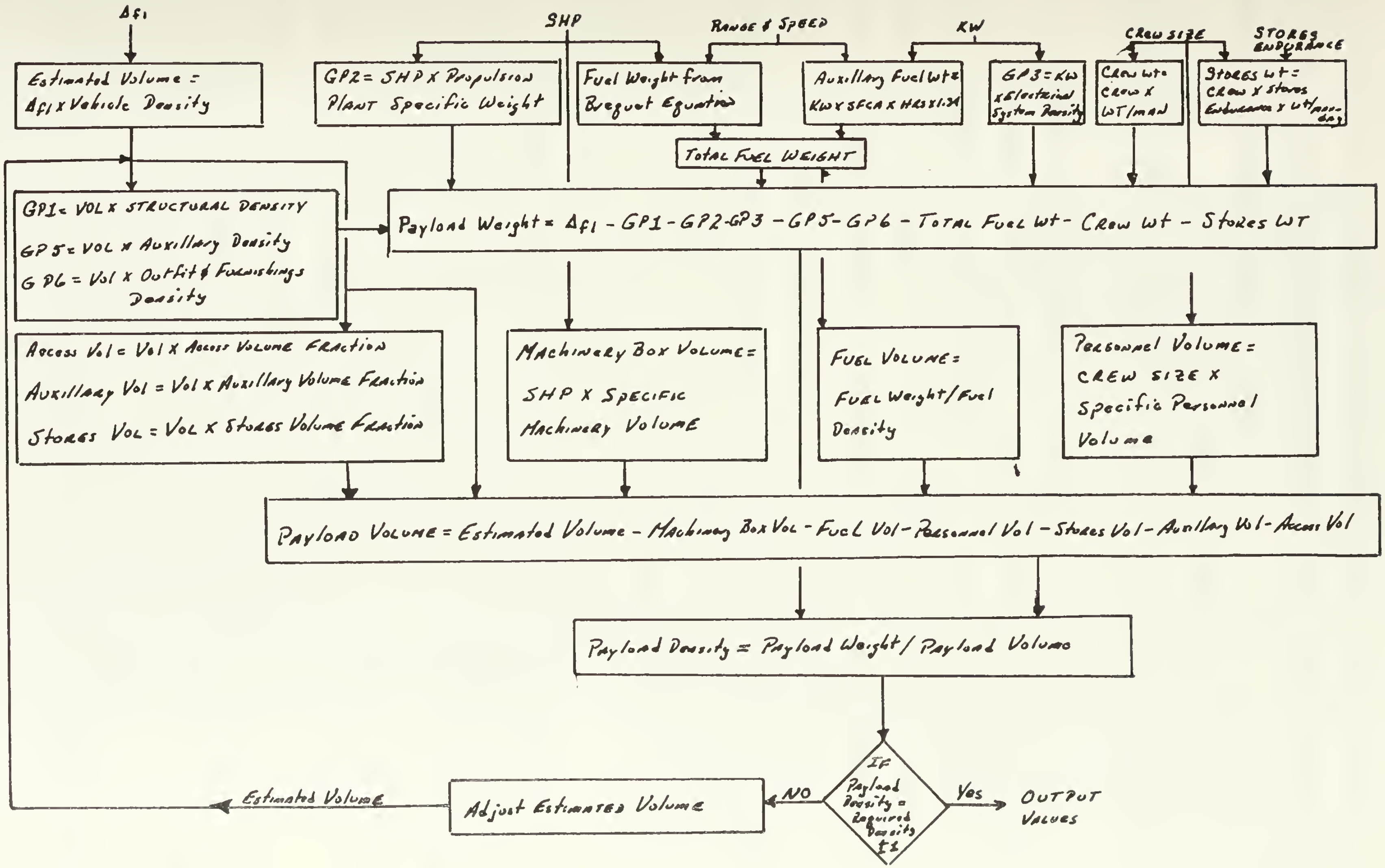

FIGURE 7 Computer Model Flow Chart

the estimated volume is incremented and another itteration is made with a new estimated volume until the requisite payload density range is met.

A flow chart for the volume algorith is contained in Figure 7 and the program listing is contained in Appendix C.

3.3.3 Limitations of the Model

The model has definite limitations since it is not a true synthesis model and does not check for feasibility in areas such as stability, large object spaces, and deck area. The model does permit the examination of the effect of a change of design parameters on a ship which is already feasible. Since the changes are in most cases distributed throughout the ship or quite flexible in their location, such as fuel, for small changes the resultant ship should have a reasonable certainty of being feasible.

The model makes the assumptions that the specific parameters applicable to a hydrofoil of a specific size are transferable to a displacement ship. To keep this assumption valid, the ships to be upgraded are of the same approximate size. Similar assumptions are made in prime mover and propulsor for main propulsion and in other areas.

The ship impact of increasing payload is accounted for in part by the parameters which are sensitive to the change in total volume required to support the payload; hull weight, outfit and furnishings weight and auxiliary systems weight.

The impact of the added payload on the electrical generation capacity is not considered. A portion of the payload weight and volume addition may be necessary to support the payload's additional electrical power requirements.

3.4 A Comparative Analysis of a Small Hydrofoil and a Planning Craft

The objective of this section is the analysis and evaluation of PHM and PG-84 as they were originally designed. From this analysis the design differences will be evaluated and then applied to redesign PG-84 to PHM design standards and performance requirements.

3.4.1 Analysis of PHM and PG-84

The PHM and PG-84, being similar in size, mission, crew size, and payload, provide a good basis for the evaluation of the ship impact of hydrofoil design standards, criteria, and philosophy. Comparing the designs as they currently exist and again with PG-84 upgraded to hydrofoil standards and requirements provides an indication of the "cost" as measured in terms of payload carrying capability for having the foil system's advantages.

The hydrofoil system's impact is quite apparent on a ship as small as PHM. The analysis procedure described in Section 3.2 was carried out for these two ships. The results of this analysis are contained in Figures 8 to 11. These figures show both the impact of the foil system and more significantly hydrofoil design standards.

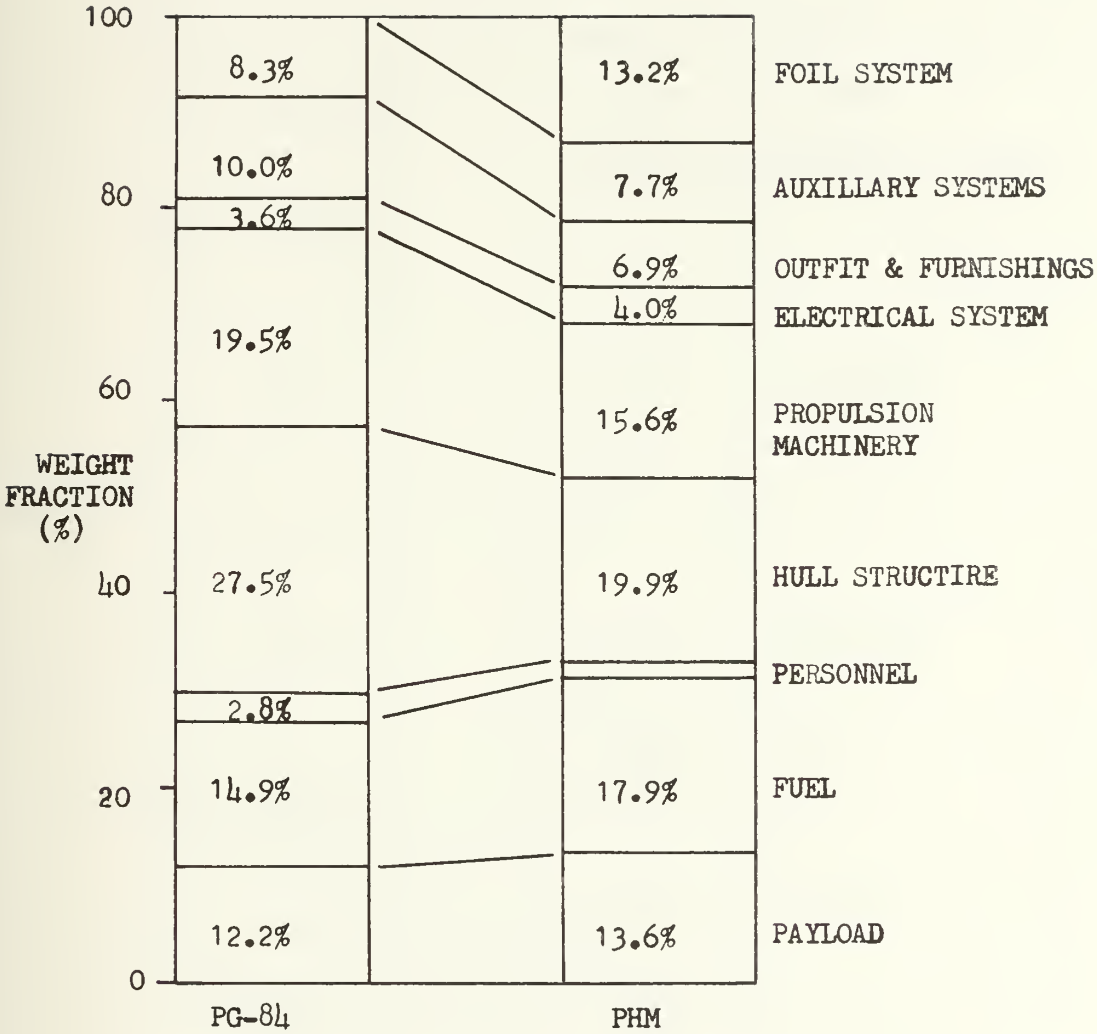

FIGURE 8 PG-84 - PHM Comparative Weight Fraction Analysis

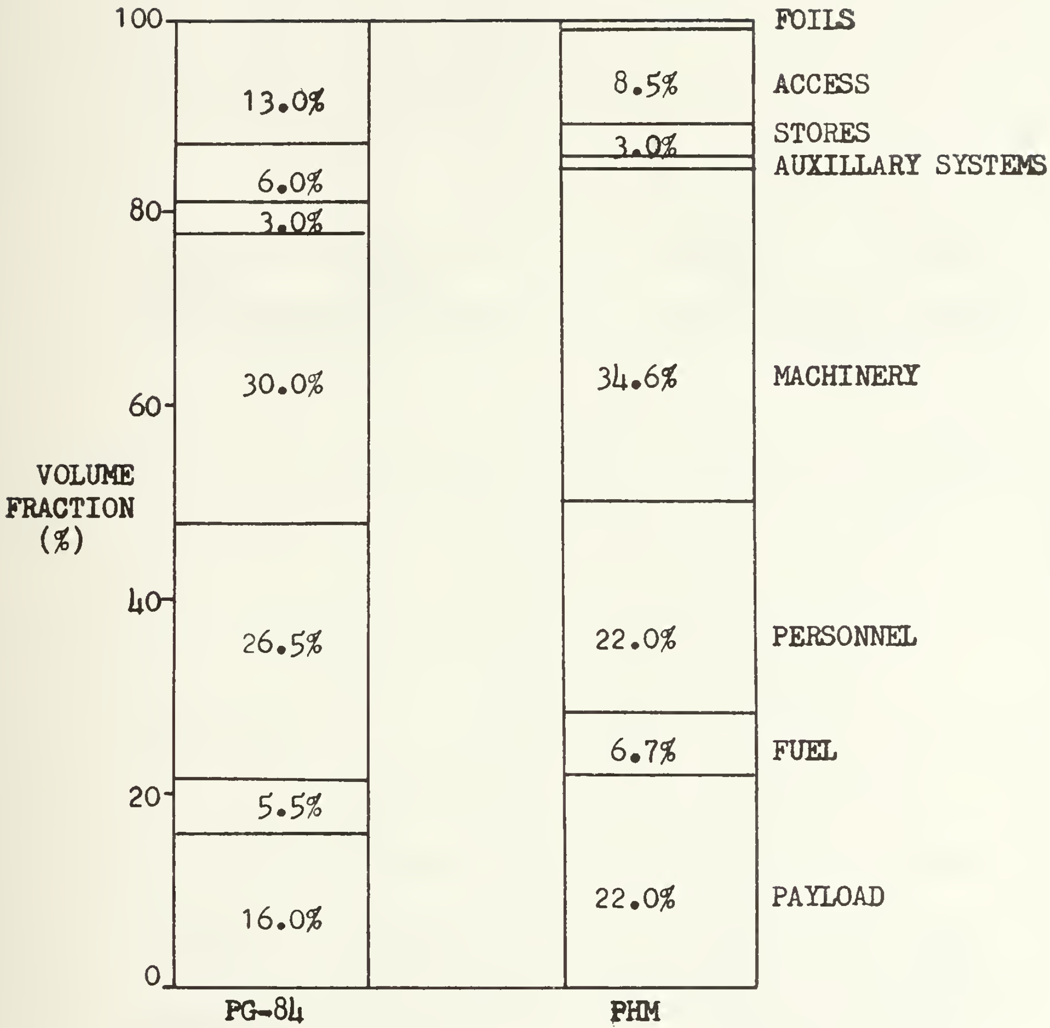

FIGURE 9 PG-84 - PHM Comparative Volume Fraction Analysis

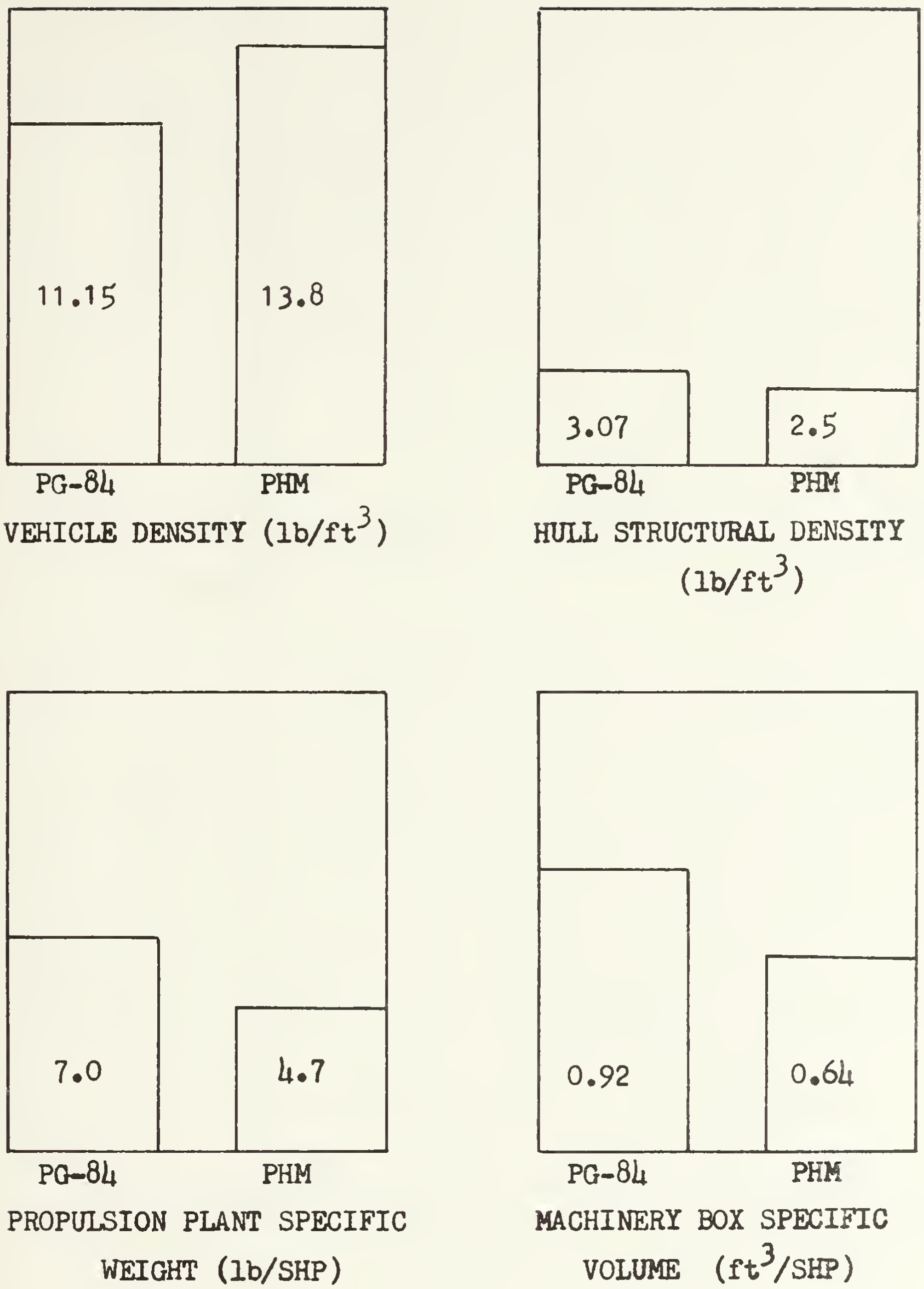

FIGURE 10 PG-84 - PHM Specific Parameters

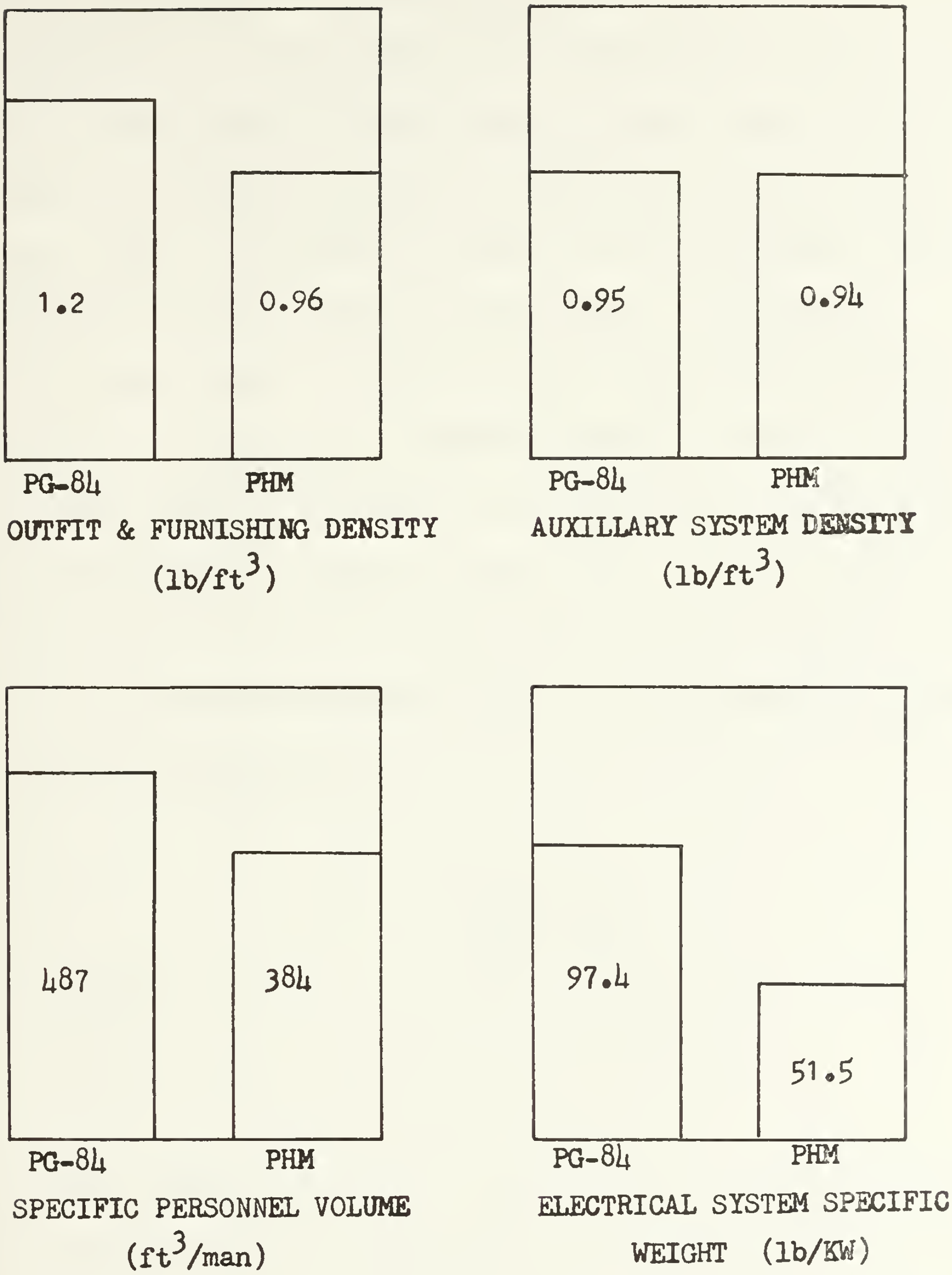

FIGURE 11 PG-84 - PHM Specific Parameters

3.4.2 Comparison of PHM and PG-84

A comparison of the weight and volume utilization provides an indication of the areas in which there are differences in design criteria or standards. It is very significant that the figure of merit, payload weight, and also payload volume is larger in PHM than in PG-84 as shown in Figures 8 and 9. This infers that the hydrofoil system was not added at the expense payload carrying capacity.

The fuel fraction or PHM is greater than PG-84. This is a reflection of both a higher speed and a longer range at high speed. A comparison on the basis of the ratio of fuel weight to a transport momentum factor (Displacement x Speed x Range) is presented below.

	$\frac{\text{lb fuel}}{\text{ton-kt-NM}}$
PG-84	1.66×10^{-2}
PHM	1.16×10^{-2}

Based on this figure of merit, PHM reflects the improvement in gas turbine technology resulting in a lower fuel consumption rate and the advantage in hydrodynamic efficiency of the hydrofoil over the planning hull at high speeds.

A more apparent difference is the smaller structural weight fraction in PHM. Even though both ships are of light-weight construction, PHM is all aluminum construction and PG-84 has an aluminum hull and fiberglass deckhouse, PHM

has significantly less weight. In both structural weight fraction and structural density PHM is less.

	Structural Weight Fraction	Structural Density
PHM	19.9%	2.5 lb/ft^3
PG-84	27.5%	3.07 lb/ft^3

The difference in structural density compared to the difference in structural weight fraction points up a second factor in the total structural weight picture. This is the impact of volume. For PG-84 the application of PHM's structural standards would reduce the hull weight by approximately 12.4 tons or 18%. Reduction of PG-84's hull volume to PHM's without changing PG-84's structural density would result in a 14.7 ton or 22% decrease. A combination of the two effects would result in the 20 ton decrease in hull weight observed between PG-84 and PHM. Thus both structural density and enclosed volume are of importance in providing the efficient use of structural weight observed in the hydrofoil.

The propulsion systems in PHM and PG-84 are significantly different even though the prime movers in both cases are diesels for low speeds and gas turbines for high speeds. PHM is waterjet propulsion and PG-84 is a subcavitating propeller. Since there are sizeable differences in the installed horsepower and type of propulsor, the specific

indices give a better picture of the weight and volume impact of the two propulsion plants.

	Machinery Plant Specific Weight	Machinery Box Specific Volume
PG-84	7.0 lb/SHP	0.92 ft^3/SHP
PHM	4.7 lb/SHP	0.64 ft^3/SHP

The electrical system is one of the best examples of the application of weight consciousness to high performance ship design. Although both PHM and PG-84 both appear to have the same electrical system weight, PHM has twice the power generation capacity. The reduction in weight is the result of a gas turbine prime mover and 400 hertz power generation in PHM in contrast with a 60 hertz system with diesel prime movers in PG-84. The difference in the electrical system specific weight is very apparent.

	Electrical System Specific Weight
PG-84	97.4 lb/KW
PHM	51.5 lb/KW

The specific densities in the area of outfit and furnishings and auxiliary systems are not significantly different from PHM to PG-84 as shown in Figure 11. The difference in weight is a result primarily from the smaller enclosed volume in PHM.

The impact of volume is very significant in the area of personnel volumes.

	Specific Personnel Volume
PG-84	487 ft^3/man
PHM	384 ft^3/man

The net decrease in displacement for the reduction of personnel volume per man on PG-84 to PHM standards, a change of approximately 100 cubic feet, would be about 5.6 tons based on PG-84 standards for structural density, outfit and furnishing density and auxiliary systems density.

The best indication of efficient volume utilization is the vehicle density. PHM with a higher vehicle density has a larger fraction of its displacement available for productive purposes since less enclosed volume implies less weight is necessary for enclosing and outfitting the hull envelope.

	Vehicle Density
PG-84	11.15 lb/ft^3
PHM	13.8 lb/ft^3

The gains to be realized from efficient volume utilization is apparent in the smaller volume fractions alloted to arrangements, access and stores on PHM. The smaller stores volume gives an indication of several areas which do not appear in the simple analysis of weight and volume. The

first is the store's endurance period. In PHM it is half of PG-84's. Although this has only a small effect on the weight utilization the volume impact is slightly larger. The second area is repair parts storerooms. PHM has no allowance for storage of spare parts in areas removed from the equipment itself. This is an indication of a basic difference in maintenance philosophy and operating profile. It carries with it a resultant effect in the overall reliability, maintainability and availability aspects of the ship.

The net result of the designers efforts is allowing PHM to absorb the weight of the foil system, representing 13.2% of the ship's displacement without impacting the payload carrying capability when compared to PG-84. The hydrofoil system allows PHM to have an edge on PG-84 in speed, endurance, and seakeeping capability. The design criteria and standards present in PHM are not unique to hydrofoils and could be equally as well applied to PG-84. In doing this the true cost, in terms of payload, of gaining the hydrofoils superior performance can be more accurately assessed. The following section examines a conceptual redesign of PG-84 to PHM standards for this purpose.

3.4.3 Redesign of PG-84 to PHM Standards

To provide the basis for a side-by-side comparison, PG-84 was conceptually redesigned to PHM standards using PHM's performance requirements and standards summarized in Table 5. These parameters were developed from the analysis

TABLE 5

PERFORMANCE REQUIREMENTS AND PARAMETERS FOR UPGRADED PG-84

	PG-84	PHM	Redesigned PG-84
Displacement (tons)	242	230	230
Maximum Speed (kts)	40(est)	45(est)	45
Range at Max. Speed	500(est)	750	750
SHP at Max. Speed	13,000(est)	15,000(est)	17,000*
Assumed Propulsion SFC	0.48[12]	0.43[13]	0.43[13]
Generator Capacity (KW)	200	400	400
Assumed Generator SFC	0.5	0.5	0.5
Crew Size	24	21	21
Store's Endurance (days)	14	7	7
Vehicle Density	11.15	13.8	(not an input)
Structural Density	3.07	2.5	2.5
Auxiliary System Density	0.95	0.94	0.94
Outfit & Furnish Density	1.2	0.86	0.86
Propulsion Plant Specific Weight	7.0	4.7	4.7
SHP Margin	unknown	unknown	1.125[8]
Electrical System Specific Weight	97.4	51.5	51.5
Machinery Box Specific Volume	0.92	0.64	0.64
Specific Personnel Volume	487	384	400
Arrangements Vol. Fraction	0.13	0.085	0.09
Auxiliary Systems Vol. Fraction	0.02	0.015	0.02
Stores Volume Fraction	0.06	0.03	0.03
Payload Density	9.3	8.75	9.0

*SHP estimate is contained in Appendix B

of PG-84 and PHM in Section 3.4.1. The one input parameter which could not be made identical is the shaft horsepower required at high speed since this is the influence of the hull type and means of sustension. The shaft horsepower required was developed from a standard series of hard chine planning craft as explained in Appendix B.

Utilizing the computer model, the weights and volumes of the redesigned PG-84 were computed. Since the performance requirements and standards were the same as PHM, the figure of merit, payload, gives the indication of the cost of the foil system in terms of payload. The results of the computer model contained in Table 6 show that the redesigned PG-84 has 13.3 tons more payload than PHM and 15.3 tons more payload than the original PG-84. To provide a comparison of the three platforms weight and volume fractions are presented in Figures 12 and 13. The only notable difference in an examination of the comparative weight and volume fractions is the fuel weight. This difference is the result of two effects. The first is the lower relative hydrodynamic efficiency of the planning hull form at this size and speed range, as discussed in Section 2.2. The second is the effect of a slightly different shaft horsepower margin which directly affects the endurance fuel requirement.

The cost of the foil system is reflected in the payload difference between the redesigned PG-84 and PHM.

TABLE 6

UPGRADED PG-84 WEIGHT AND VOLUME ESTIMATE

	Weight (tons)	Weight Fraction
Group 1	45.28	0.197
Group 2	35.67	0.155
Group 3	9.20	0.040
Group 5	17.02	0.074
Group 6	15.57	0.068
Payload	44.81	0.195
Personnel	2.81	0.012
Stores	0.75	0.003
Fuel	58.98	0.256
Total	230	

	Volume (Cubic Ft)	Volume Fraction
Machinery Box Volume	12240	0.302
Auxiliary System Volume	811	0.020
Access Volume	3651	0.090
Payload Volume	11250	0.277
Personnel Volume	8400	0.207
Stores Volume	1217	0.030
Fuel Volume	2998	0.074
Total Volume	40567	

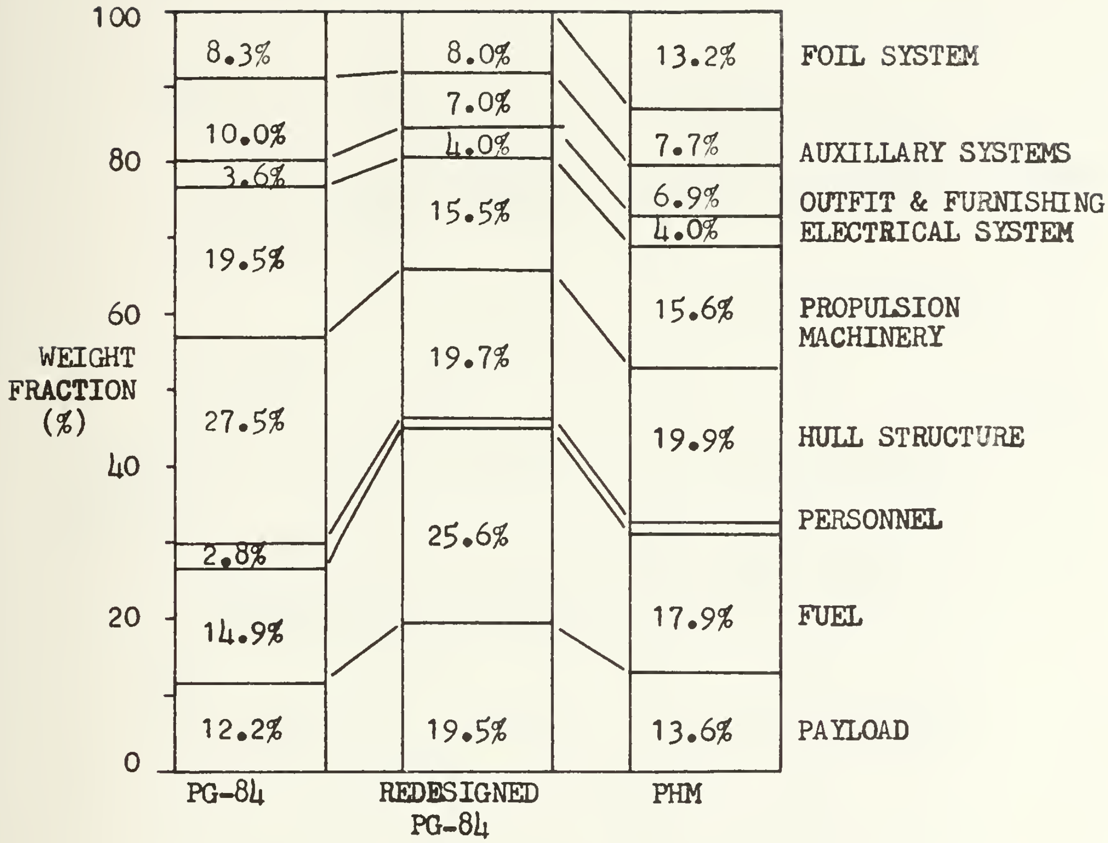

FIGURE 12 Comparative Weight Fractions for Upgraded PG-84

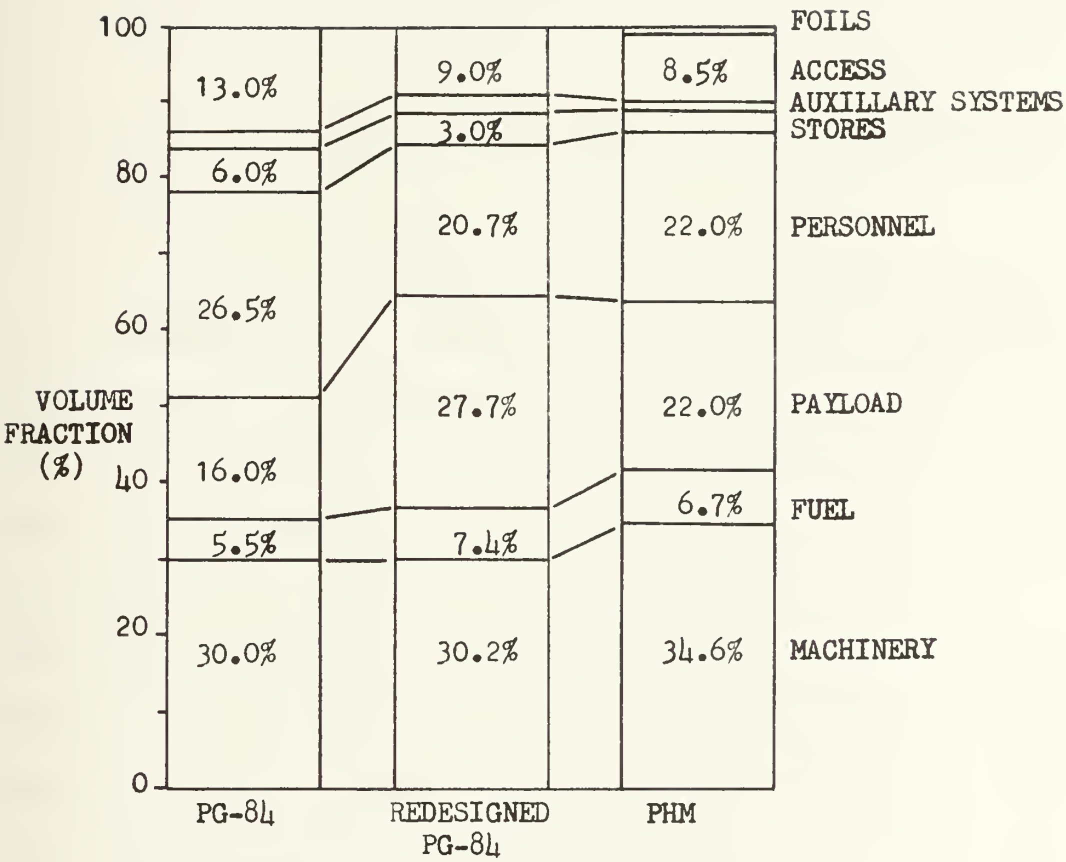

FIGURE 13 Comparative Volume Fractions for Upgraded PG-84

	Payload Weight Fraction	Payload Weight Tons	Payload Weight Difference
PG-84	12.2%	29.5	-15.3
Redesigned PG-84	19.5%	44.8	--
PHM	13.6%	31.5	-13.3

In return for this cost is the ability to maintain speed in a sea state.

To evaluate the advantage of this sea state capability, the redesigned PG-84's seakeeping capability at high speed was estimated from the data presented by Savitsky in Reference 14. PG-84 at 45 knots is operating at a speed length ratio where the added resistance due to waves is almost a constant twenty percent greater than the calm water resistance. This increase in resistance does not provide the limiting speed in a sea state but rather the acceleration forces. For a sea state 5, significant wave height of 5.5 feet, accelerations of the center of gravity on the order of 1 g could be expected at a speed of 45 knots. To reduce the acceleration levels to a tolerable level, 0.5 g [3], requires slowing to about 20 knots. However, in sea state 3, significant wave height of 2.5 feet, there is only a slight increase in added resistance, on the order of 10% and the accelerations are on the order of 0.2 g.

From an operational point of view the planning hull form would have to slow below its maximum speed more than 50% of the time in the North Atlantic based on its year around sea state profile [15]. The hydrofoil could operate in excess of 90% of the time with no appreciable speed loss.[7]

3.4.4 Sensitivity Analysis of Redesigned PG-84

During the analysis of the redesigned PG-84 it became apparent that the figure of merit was very sensitive to certain parameters. To explore this more completely, the computer model was used to test the sensitivity of the payload to changes in individual parameters and to the change of several parameters at once.

The change in payload fraction for a variation of a single parameter holding all other parameters constant was computed for a change in required shaft horsepower, shaft horsepower margin, propulsion plant specific weight, specific fuel consumption rate, structural density, specific personnel volume, and payload density. The composite results are shown in Figure 14. The impact of the mobility related parameters is pronounced and shows the impact hydrodynamic efficiency has on the ability to carry payload.

To investigate the effect of the variation of more than one parameter, shaft horsepower required, specific fuel

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[7]Based on Figure 2 for sea state 6 which occurs less than 10% of the time in the North Atlantic [15].

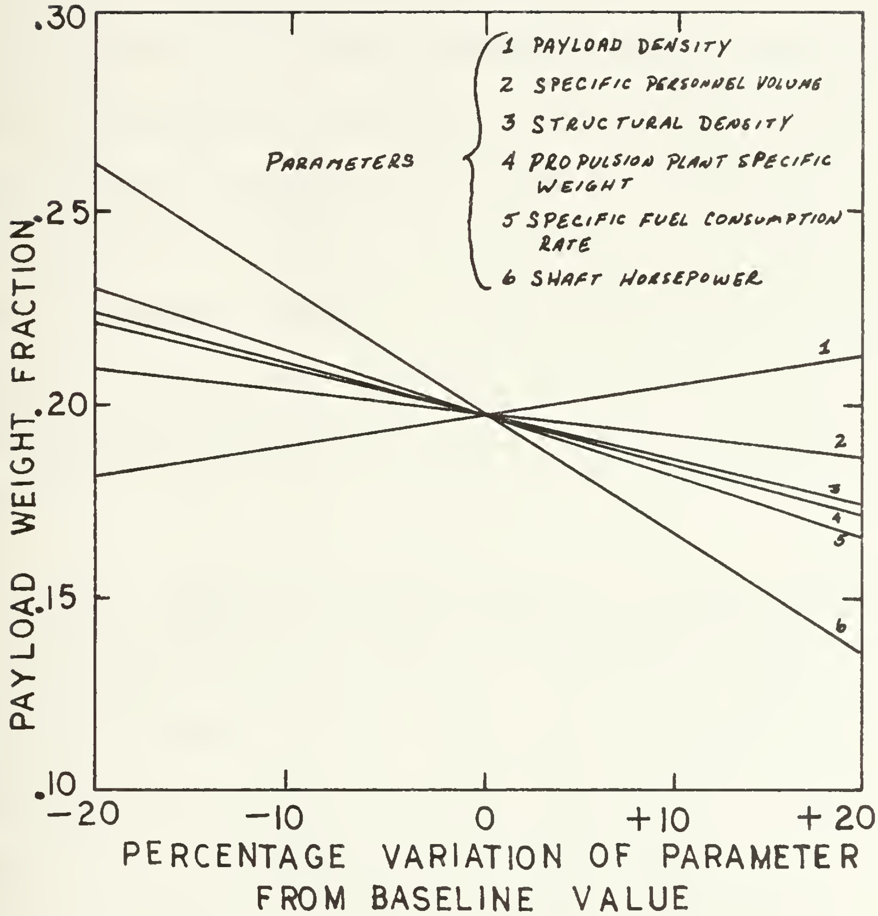

FIGURE 14 Sensitivity Analysis of Upgraded PG-84 to Single Parameter Changes

consumption rate, structural density, propulsion plant specific weight, specific personnel volume and payload density were all varied in one percent increments of the original value. All the parameters except those six selected were held constant at the original value. The results of this analysis are shown in Figure 15. This analysis indicates that a 5% variation in these six major parameters still results in a payload fraction greater than PHM. Thus with a 5% error in the estimates for these parameters the redesigned PG-84 would still have a larger payload.

3.4.5 Summary of the Analysis of PG-84 and PHM

The comparison of PG-84 and PHM point out differences in several design areas. The areas of greatest apparent difference are propulsion plant weight and volume, personnel volume, and arrangements and access volume. In all these areas PHM showed a marked advantage. There was a lesser but yet significant difference in the areas of hull structural weight and electrical system weight. The net result was the accommodation of the foil system without an adverse effect on payload carrying capability.

To determine the "cost" of the foil system in terms of payload carrying capability, the PG-84 was conceptually redesigned to the same performance requirements, criteria and standards as PHM. The only significant difference between the two is the hull form and foil system and thus

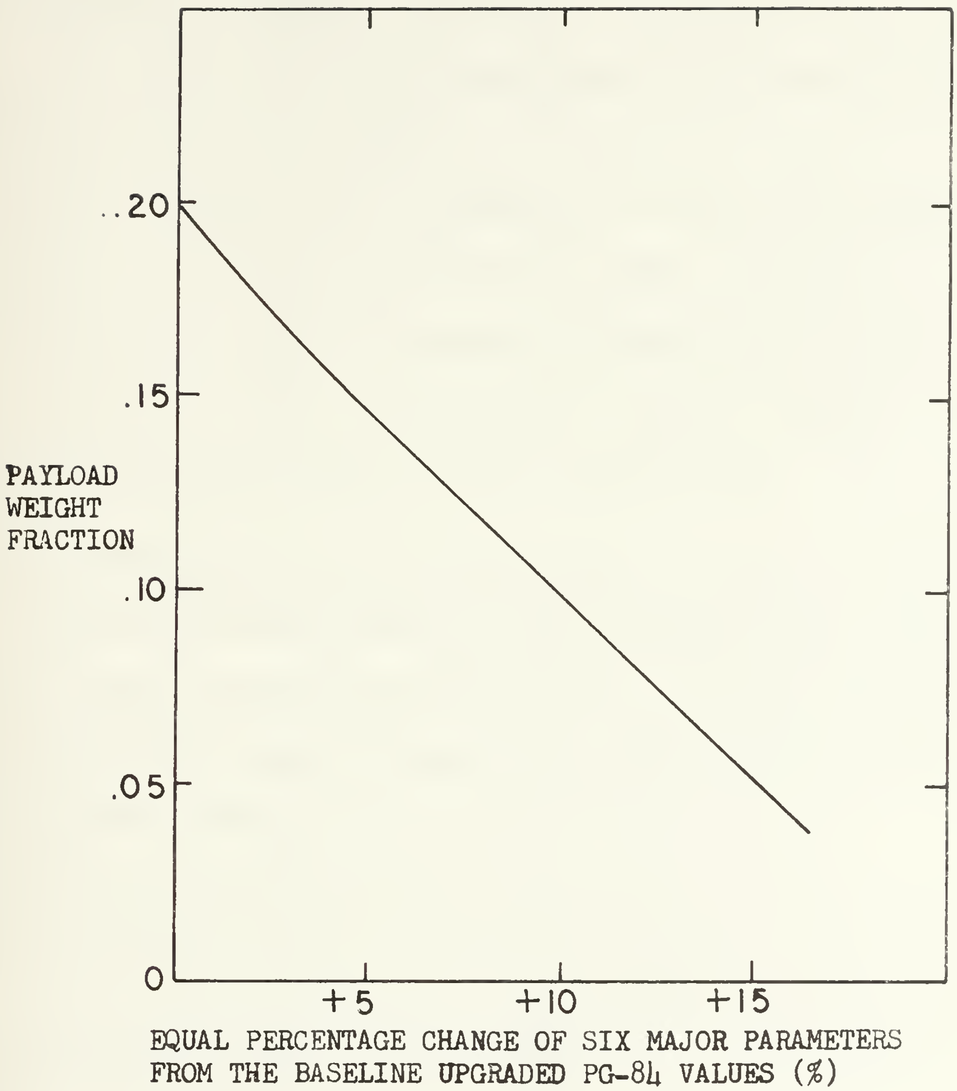

FIGURE 15 Sensitivity Analysis of Upgraded PG-84 to Multiple Parameter Changes

the propulsive power requirement. The comparison was then made based on the weight of payload carried as the figure of merit. The results of the comparison of PHM and the redesigned PG-84 are summarized below.

- PG-84 (redesigned) is capable of carrying 42 percent or 13.5 tons more payload than PHM. However, a fraction of the additional payload weight may be required to provide additional payload support such as electrical power or air-conditioning.

- The redesigned PG-84 is required to reduce speed from its maximum speed at approximately sea state 3 to avoid excessive accelerations. PHM can maintain its maximum speed through sea state 5 and probably into sea state 6.

- The redeisgned PG-84 requires more fuel to cover the same endurance range at high speed due to its poor hydrodynamic efficiency compared to the hydrofoil.

This demonstrates the tradeoff between seakeeping ability as manifested by the ability to maintain speed in the higher sea states and the ability to carry payload. For the small ship case there is no obvious best. The selection must be predicted on the ship's operating profile and area of intended operations.

3.5 A Comparative Analysis of A Large Hydrofoil and A Displacement Ship

3.5.1 Analysis of DEH and FFG-7

Unlike the comparison of PHM and PG-84, there are significant differences in both size, a factor of three, and speed, a factor of two, between DEH and FFG-7. Although this makes comparison of some features of questionable significance, it still lends insight into the wide gulf between the conventional surface combatant and a hydrofoil with the same relative mission capabilities.

The overhead involved with the foil system is not as readily judged due to the differences in size. The impact of the DEH's speed and endurance is much more apparent. The analysis of the two designs was conducted using the methods described in Section 3.2. The results of this analysis are contained in Figures 16 to 19.

3.5.2 Comparison of DEH and FFG-7

An inspection of the weight and volume utilization on DEH and FFG-7 shows the marked difference between a displacement ship and a hydrofoil. Examining the relative weights and volumes, the differences in size and speed must be considered. Although the mission areas are the same and the capabilities are very similar, the effects of size and speed tend to bias the relative magnitudes in both the weight and volume analyses.

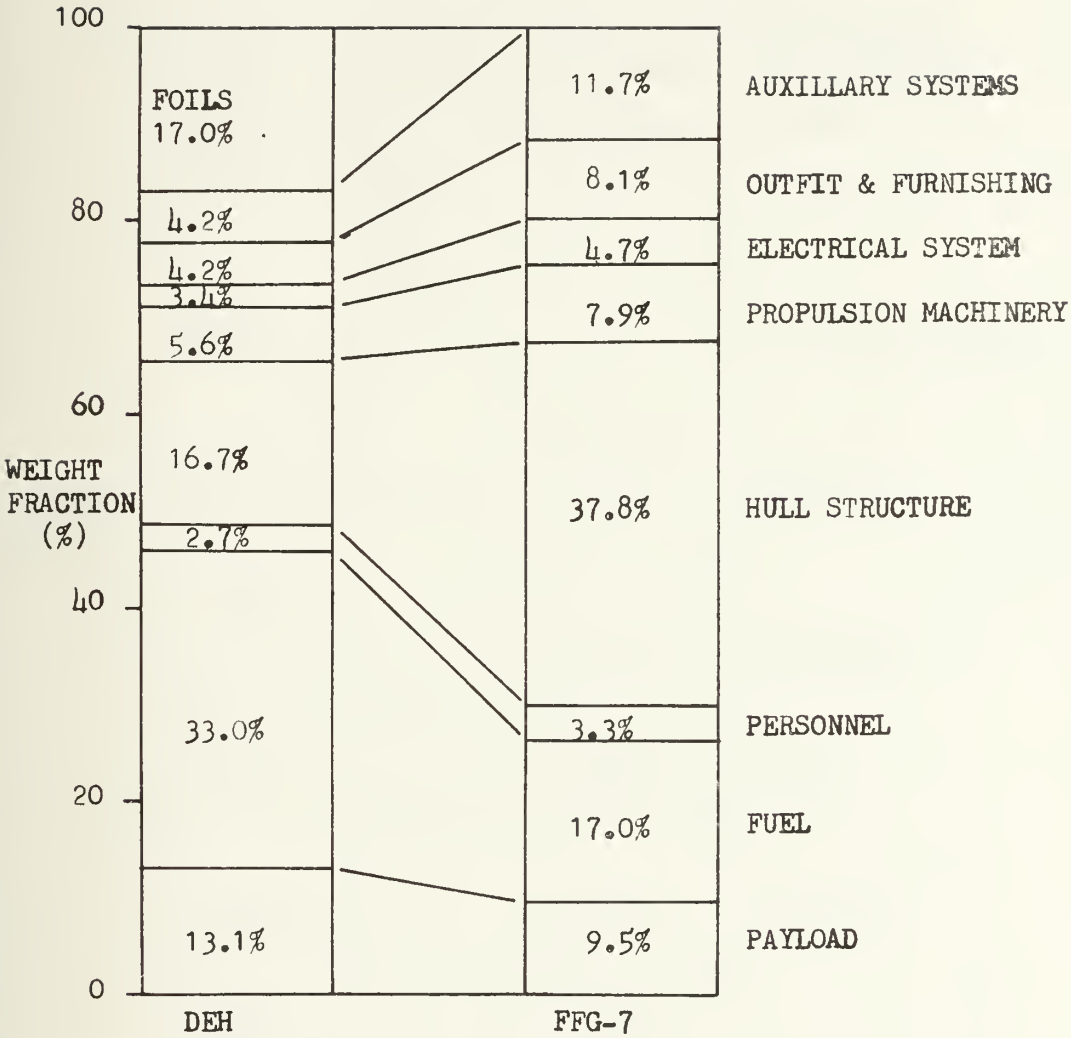

FIGURE 16 DEH - FFG-7 Comparative Weight Fraction Analysis

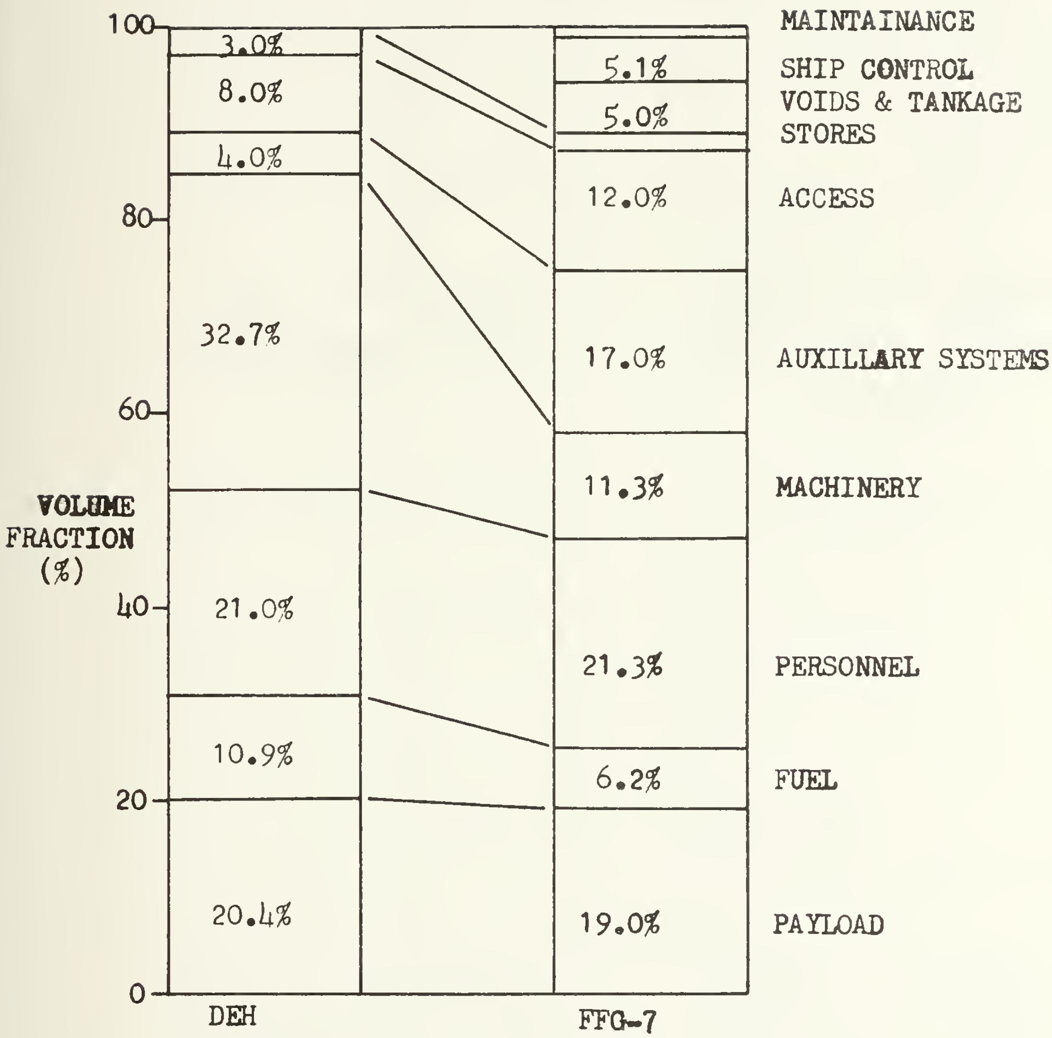

FIGURE 17 DEH - FFG-7 Comparative Volume Fraction Analysis

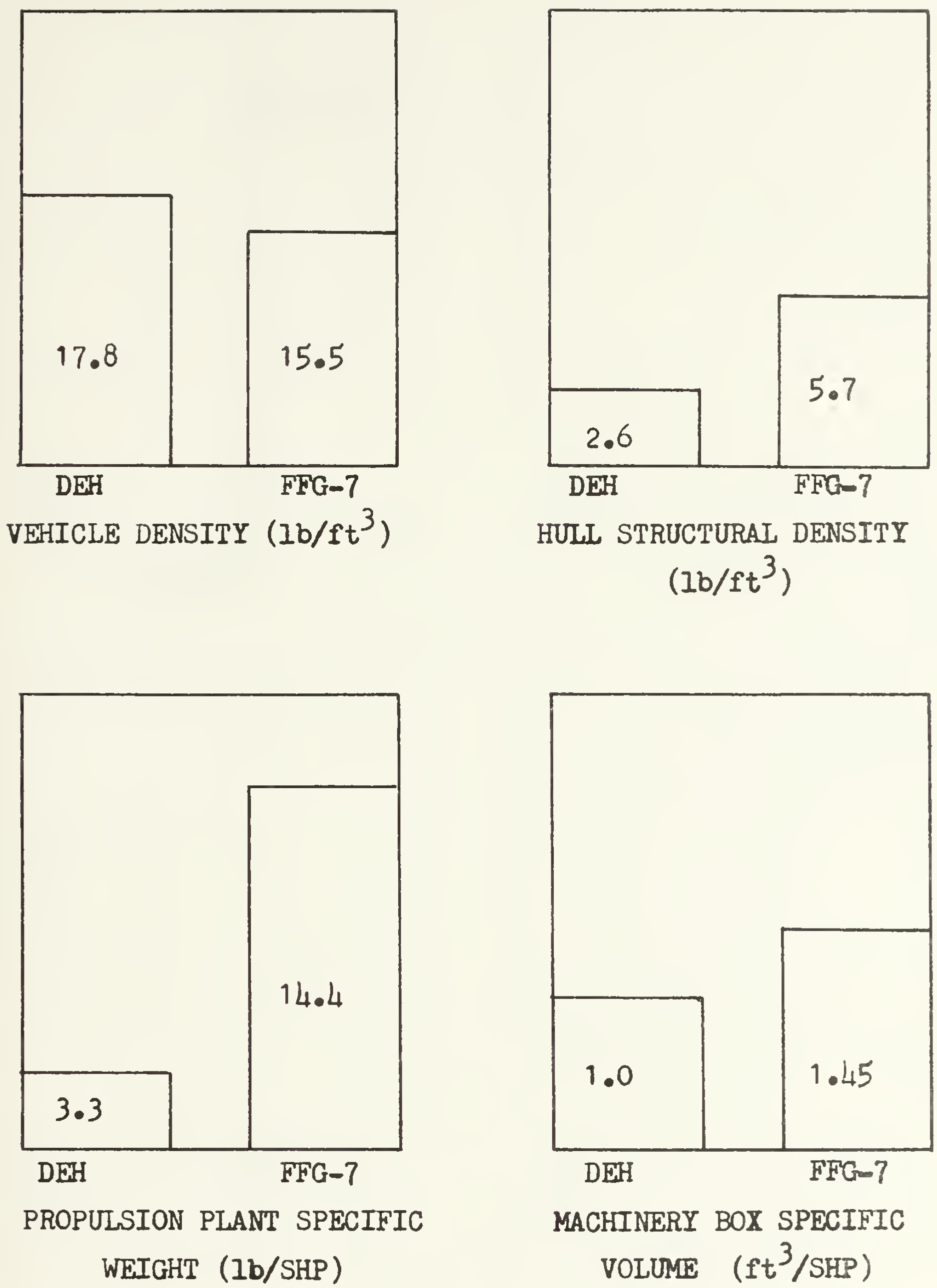

FIGURE 18 DEH - FFG-7 Specific Parameters

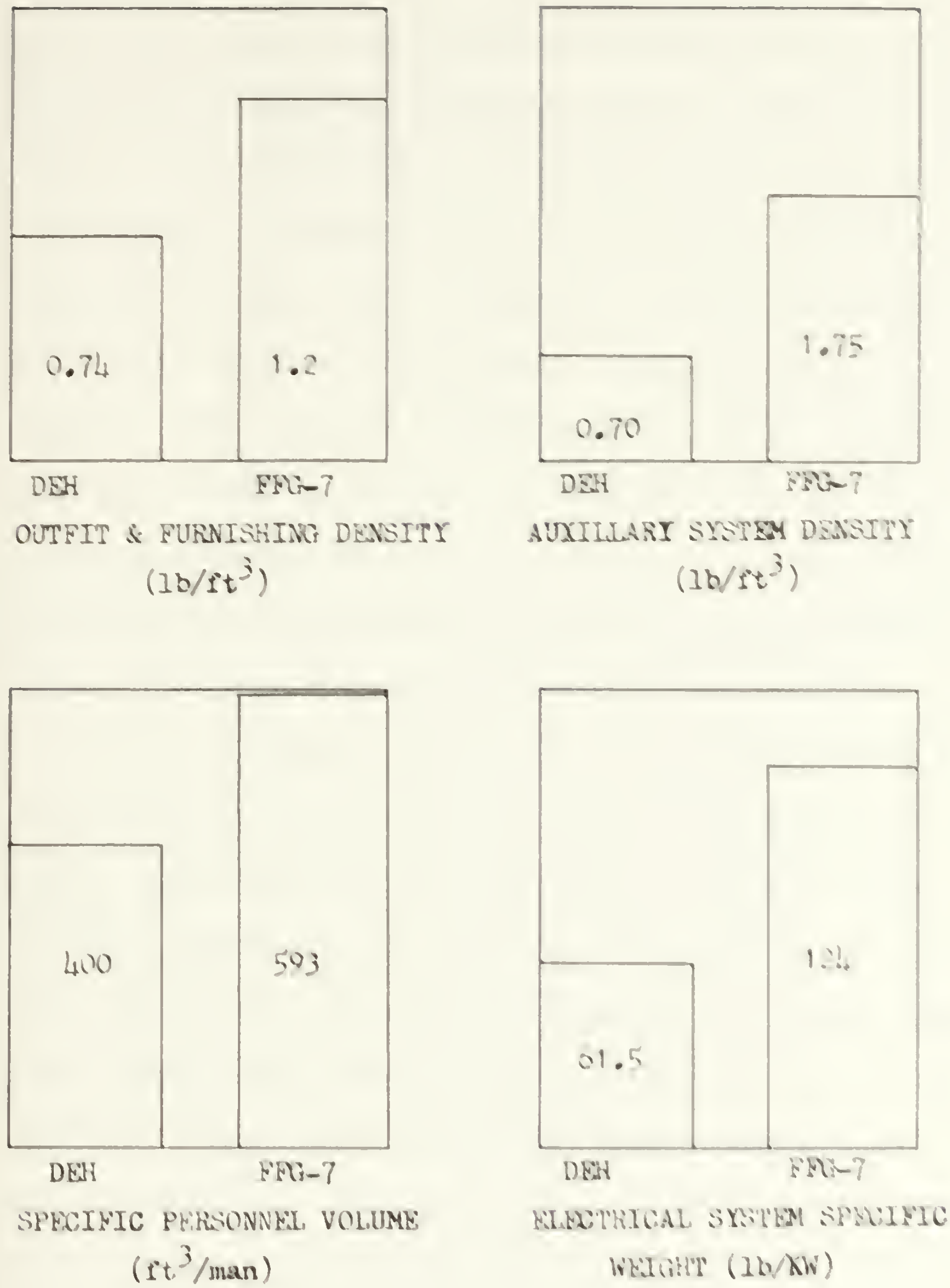

FIGURE 19 DEH - FFG-7 Specific Parameters

The measure of effectiveness, payload weight is most revealing. DEH has a larger payload weight fraction than FFG-7 with about the same volume fraction. The weight difference is not disputable, for DEH has a significant number of weapons systems which are by necessity compact. FFG-7 has many of the same or similar weapons systems but also has a large volume requirement imposed by two helicopters. DEH is still significantly better in terms of the measure of effectiveness. It should be noted that a twelve percent payload fraction is representative of many of the more recent displacement ship designs and thus FFG-7 rather than DEH is a variation from the norm [16].

The effect of speed appears in two areas. The fuel volume is a direct indication of the DEH's requirement for high speed. The large weight fraction alloted to fuel, 33%, reflects the requirement for both high speed and a long endurance range at high speeds. FFG-7 with a much lower speed requirement but longer endurance results in a lower fuel fraction. The other area which speed impacts is propulsion machinery. The machinery weight fraction for both ships is small reflecting the impact of gas turbines. Examining the propulsion plant specific weight, however, shows that there is a significant difference. The impact on DEH is more apparent in the volume analysis where about 33% of the total volume is propulsion machinery, electrical generators, and propulsion auxiliaries. The other point of

interest is both ships have identical main propulsion prime movers and are fitted with propellers as propulsors rather than having a waterjet for the hydrofoil. The propulsion comparison can be summarized as follows:

	DEH	FFG-7
Propulsion Weight Fraction	5.6%	7.3%
Machinery Volume Fraction	32.7%	11.3%
Propulsion Plant Specific Weight	3.3 lb/SHP	14.4 lb/SHP[8]
Machinery Box Specific Volume	1.0 ft^3/SHP	1.45 ft^3/SHP

Examining the other weight groups shows the trends which were also apparent in the comparison of PHM and PG-84 in Section 3.4.2. There is again a marked reduction in both the weight fraction and specific weight in the areas of outfit and furnishings and auxiliary systems.

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[8]The factor of 4 difference in propulsion plant specific weight is an area of major impact at the horsepower levels required by these ships (50,000 SHP). The areas of weight saving are numerous including lightweight reduction gears and shafting, less sound isolation, and shorter lengths of intake and exhaust ducting.

	DEH	FFG-7
Outfit & Furnishing Weight Fraction	4.2%	8.0%
Outfit & Furnishing Density	0.74 lb/ft^3	1.2 lb/ft^3
Auxiliary System Weight Fraction	4.2%	11.6%
Auxiliary Systems Density	0.70 lb/ft^3	1.75 lb/ft^3

Unlike the comparison of PHM and PG-84 in Section 3.4.2, there is a significant difference in the structural area beyond the state of the art in lightweight structural design. FFG-7 with a steel hull and aluminum deckhouse is significantly heavier than the all aluminum DEH. This is reflected in both the weight fraction and structural density.

	DEH	FFG-7
Structural Weight Fraction	16.7%	37%
Structural Density	2.6 lb/ft^3	5.7 lb/ft^3

The very high structural weight fraction again reflects the cost of excessive volume. For most destroyer designs the structural weight fraction is in the range of 26 to 32% (see Figure 4, Section 2.2). This impact cannot be overlooked if a high speed displacement hull is desired.

The effect of size and more importantly volume is reflected in many areas. The first indication is vehicle density.

	DEH	FFG-7
Vehicle Density	17.8 lb/ft^3	15.5 lb/ft^3

A large amount of unproductive space is the first indication of the cause for the low vehicle density in FFG-7. Access, voids and tankage, and store's volume in FFG-7 all contribute to the low vehicle density as well as the large hangar required for the relatively light helicopter. This largely underutilized space is too costly to be allowed on a hydrofoil where volume carries with it a more significant weight penalty. Similarly, the volume provided for the crew carries a weight penalty and thus the hydrofoil reflects the impact of this volume in its specific personnel volume.

	DEH	FFG-7
Specific Personnel Volume	400 ft^3/man	593 ft^3/man

The cost of volume can be illustrated by assuming a reduction in personnel volume standards on FFG-7 to the standards of DEH while making no changes in any of FFG-7's other design criteria. The net change in volume of

200 ft^3/man for the 185 man crew results in a 143 ton change in displacement or an equilvalent addition of payload assuming no additional payload volume is required. For FFG-7 this represents approximately a 50% increase in payload weight.

The differences which might have been attributed to a different operating profile in the case of PHM and PG-84 are not truly present here. Both ships are designed for long open ocean transits and to be self-sustaining over extended periods of time. The significant differences other than size and speed and their ramafications have been pointed out in this section. The result appears to be a smaller, faster ship which has the same mission capabilities as a ship three times its size and half its speed. The overhead of the foil system appears to be well justified and has given the ship significant capabilities.

3.5.3 Redesign of A Displacement Hull Form to DEH Standards

The redesign of the FFG-7 was attempted with the computer model to provide an indication of the impact hydrofoil design standards would have on a displacement hull form. The FFG-7's original parameters and the ones used to upgrade the standards to hydrofoil standards are contained in Table 7. The model was used to predict two ships. The first was an FFG-7 with DEH's payload fraction searching for the maximum speed. The second was a ship with FFG-7's speed and searching for the payload fraction. The results are presented graphically in Figure 20.

TABLE 7

PERFORMANCE REQUIREMENTS AND PARAMETERS FOR UPGRADED FFG-7

	DEH	FFG-7	FFG-7 to DEH Standards
Displacement	1220	3450	3450
Maximum Speed	~45	28.5	--
Range at Maximum Speed	2600	~2000	2600
SHP	~40,000	~32,000	--
Assumed Propulsion SFC	0.43[13]	0.43[13]	0.43[13]
Generator Capacity	1500	2000	2000
Assumed Generator SFC	0.5	0.5	0.5
Crew Size	82	185	185
Store's Endurance	45	45	45
Vehicle Density	17.8	15.5	--
Structural Density	2.6	5.7	2.6
Auxiliary Systems Density	0.70	1.75	0.70
Outfit & Furnishing Density	0.74	1.2	0.74
Propulsion Plant Specific Wt.	3.3	14.4	3.3
SHP Margin	--	1.25	1.25
Electrical System Specific Wt.	61.5	125	61.5
Machinery Box Specific Vol.	1.0	1.45	1.0
Specific Personnel Volume	400	593	400
Arrangements Volume Fraction	0.08	0.22	0.08
Auxiliary Systems Volume Fraction	0.04	0.17	0.04
Store's Volume Fraction	0.03	0.02	0.03
Payload Density	11.7	--	11.7

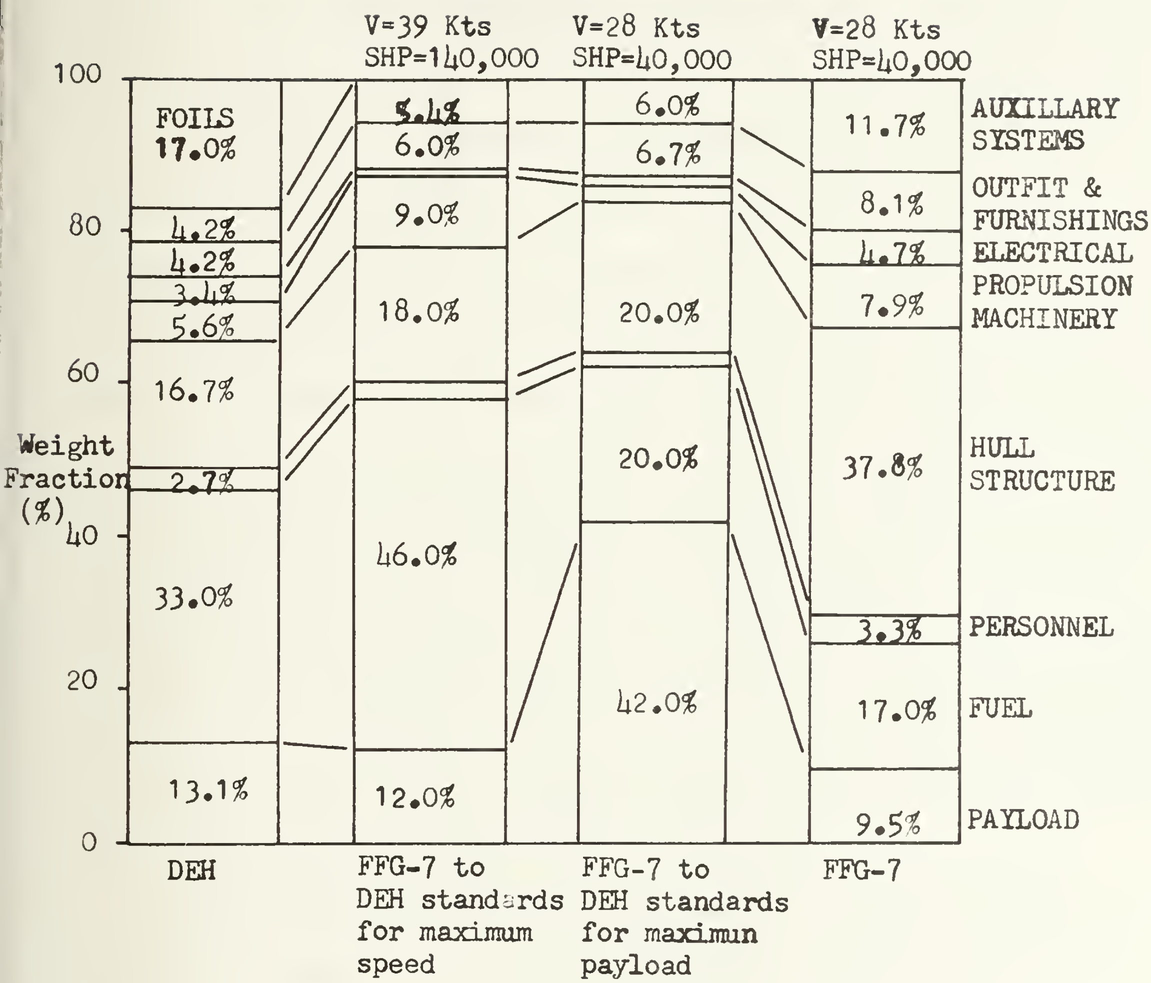

FIGURE 20 Upgraded FFG-7 Comparisons

For the first case the maximum speed was estimated at about 39 knots with 140,000 shaft horsepower required. In the second case the resultant payload was about 1445 tons or 42 percent of full load displacement. These results are not intended to be accepted as feasible designs. They do, however, show the significant impact which hydrofoil technology could have on the conventional displacement ship.

To provide a side-by-side comparison, a powering estimate for a 1200 ton series 64 hull form was made. This estimate is contained in Appendix B. From the estimate of 50,000 shaft horsepower for a 1200 ton ship at 45 knots, a ship was conceptually designed to DEH standards. The inputs to the computer model for this analysis are shown in Table 8 and the results in Figures 21 and 22 and Table 9. Again the only major area of difference is fuel weight. This may reflect the conservatism in the selection of shaft horsepower required for maximum speed and specific fuel consumption rate. If this is the case a smaller required fuel weight would be almost directly transferable to payload.

Even with the large difference in required fuel the Series 64 hull form has a larger payload fraction and a sizeable increase in payload.

	Payload Weight Fraction	Payload Weight (tons)
DEH	0.131	160
SERIES 64	0.159	191

TABLE 8

PERFORMANCE REQUIREMENTS AND PARAMETERS FOR SERIES 64 HULL FORM

	DEH	SERIES 64
Displacement	1220	1200
Maximum Speed	~45	45
Range at Maximum Speed	2600	2600
SHP	~40,000	50,000*
Assumed Propulsion SFC	~0.43[13]	0.43[13]
Generator Capacity	1500 KW	1500 KW
Assumed Generator SFC	0.5	0.5
Crew Size	82	82
Store's Endurance	45	45
Vehicle Density	17.8	17.8
Structural Density	2.6	2.6
Auxiliary Systems Density	0.7	0.7
Outfit & Furnishing Density	0.74	0.74
Propulsion Plant Specific Weight	3.3	3.3
SHP Margin	--	1.125[8]
Electrical System Specific Wt.	61.5	61.5
Machinery Box Specific Volume	1.0	1.0
Specific Personnel Volume	400	400
Arrangement Volume Fraction	0.08	0.08
Auxiliary Systems Volume Fraction	0.04	0.04
Store's Volume Fraction	0.03	0.03
Payload Density	11.7	11.7

*SHP estimate contained in Appendix B.

TABLE 9

SERIES 64 WEIGHT AND VOLUME ESTIMATE

WEIGHTS

	Weight (tons)	Weight Fraction
Group 1	210.81	0.176
Group 2	73.66	0.061
Group 3	41.18	0.034
Group 5	56.76	0.047
Group 6	60.00	0.050
Payload	191.00	0.159
Personnel	10.98	0.009
Stores	13.18	0.011
Fuel	542.43	0.452
Displacement	1200.00	

VOLUMES

	Volume (Cubic Feet)	Volume Fraction
Machinery Box Volume	56250	0.31
Auxiliary Systems Volume	7265	0.04
Access Volume	14530	0.08
Payload Volume	37712	0.208
Personnel Volume	32800	0.181
Store's Volume	5449	0.030
Fuel Volume	27615	0.152
Total Volume	181620	

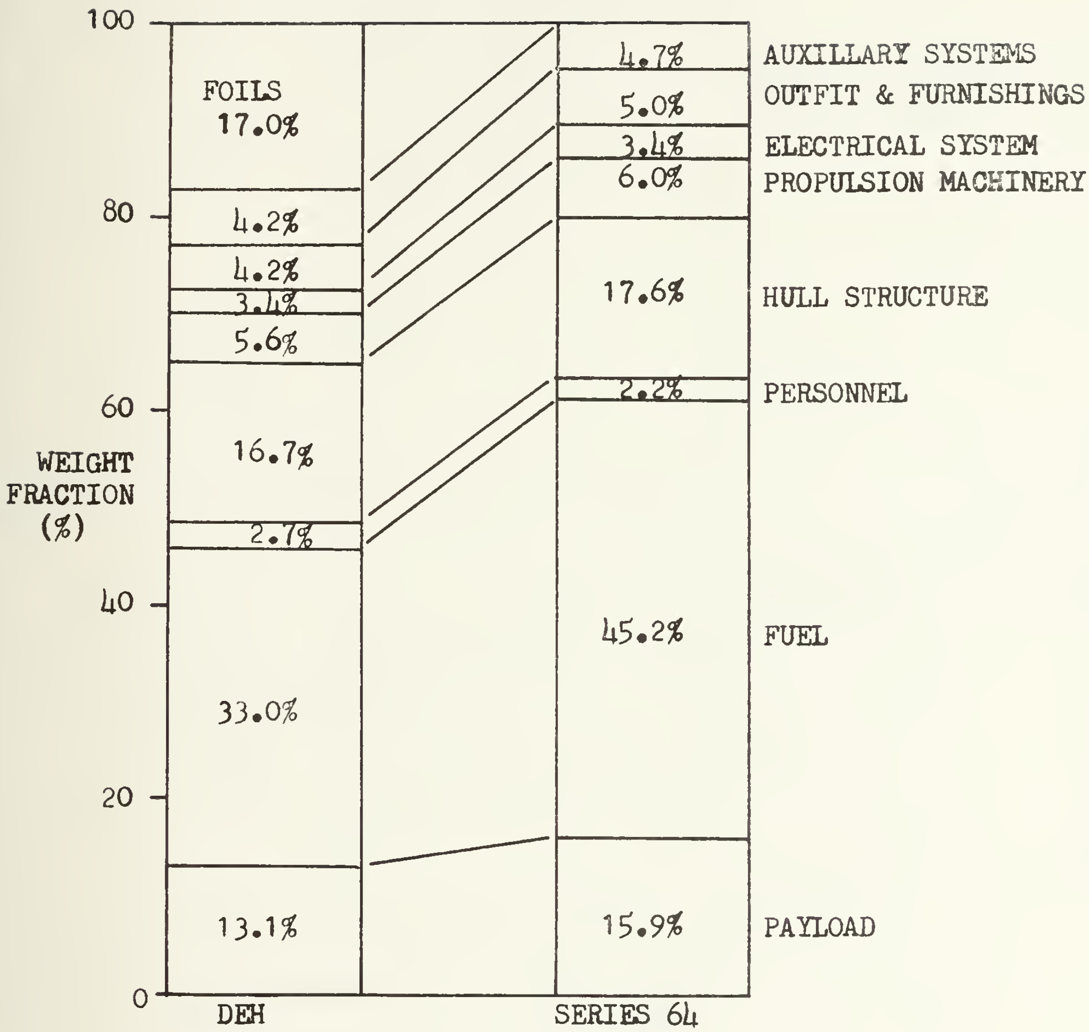

FIGURE 21 Comparative Weight Fractions for Series 64 and DEH

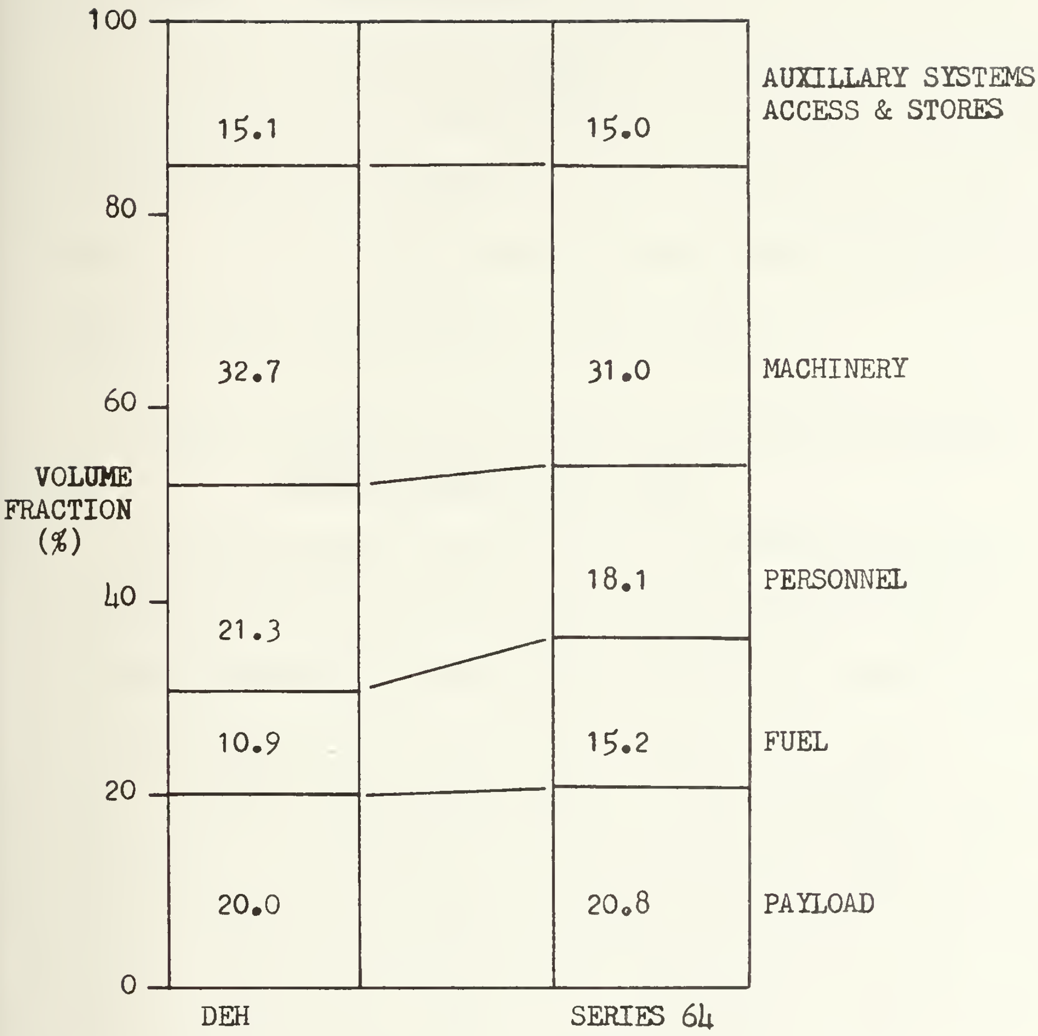

FIGURE 22 Comparative Volume Fractions for Series 64 and DEH

Although the increase in the payload weight fraction is less than that experienced with the PG-84 case, 21 percent as opposed to 42 percent for PG-84, the net increase of 31 tons of payload is substantial.

The other important aspect of the large fuel fraction is the endurance at lower speeds. The large fuel fraction for the Series 64 results in an endurance at 20 kts. in excess of 5000 N.M.[9] This is about 1000 N.M. greater endurance than estimated for DEH at 19 kts.[15].

3.5.4 Sensitivity Analysis of the High Speed Displacement Hull Form

The large fuel fraction for the Series 64 hull form raised questions on the sensitivity of the figure of merit to small changes in the propulsion plant characteristics at the high speeds and long endurance ranges required of this ship. To give some indication of the effect required shaft horsepower and specific fuel consumption rate have on the payload fraction, a sensitivity analysis was made with the computer model for these two parameters. The results of the analysis are shown in Figure 23.

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[9]Based on the horsepower estimate in Appendix B of 7000 SHP at 20 kts. and a steady 1200 KW electrical load resulting in approximately an additional 2000 hp, the maximum range is about 5100 N.M. using a 0.5 all purpose fuel rate.

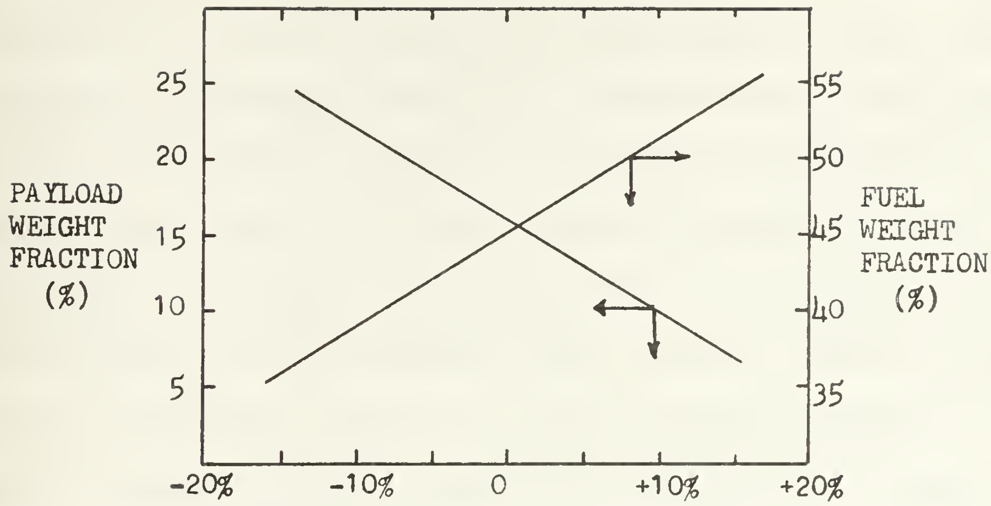
A decrease in required shaft horsepower of 10 percent results in a 20 percent improvement in payload fraction and a reduction of the fuel fraction to 42 percent. A similar 10 percent decrease in specific fuel consumption rate results in a 13.7 percent increase in payload fraction.

The combined result of changing both the required shaft horsepower and the specific fuel consumption rate by 10 percent is a 31 percent increase in payload fraction. In this case the fuel fraction is 38.9 percent which is similar to DEH which is expected for ships with approximately the same lift-drag ratio at this speed.

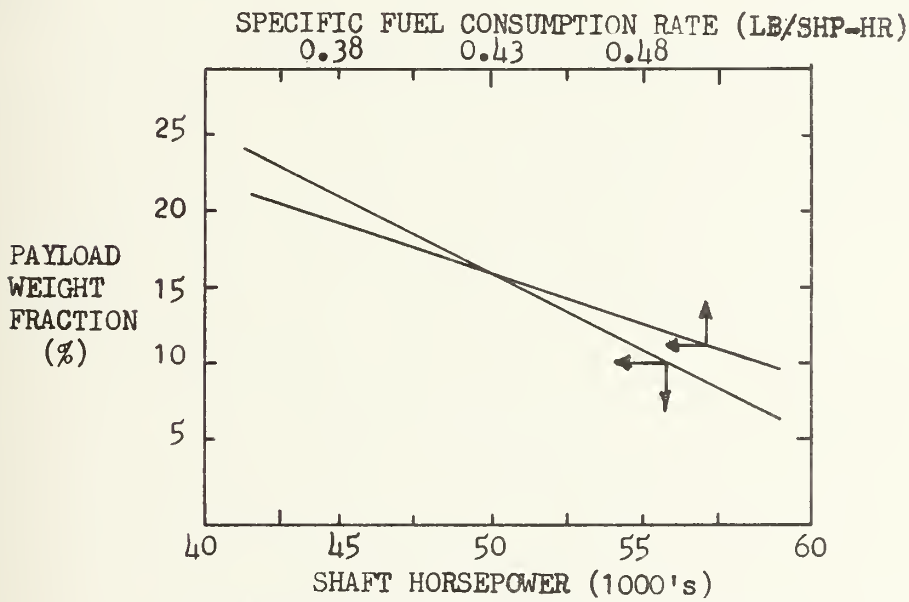
3.5.5 Summary of the Analysis of DEH and FFG-7

The size difference between DEH and FFG-7 overshadowed much of the comparison of the two ships. It did point out the wide variance between displacement ship standards and hydrofoil standards, but it would not permit a side-by-side comparison. To provide a side-by-side comparison a 1200 ton Series 64 hull form was used to provide a powering estimate. Utilizing this as an input, a 1200 ton displacement ship was conceptually designed for the comparison.

The impact of hydrofoil technology on a large displacement ship was assessed by examining the payload fraction or maximum speed arrived at by designing FFG-7 to DEH standards. The results were a 28 knot destroyer with a 42 percent payload weight fraction or a 39 knot destroyer with a 12 percent



SENSITIVITY TO EQUAL PERCENTAGE CHANGE
IN SFC AND SHP FROM BASELINE SERIES 64



SINGLE PARAMETER SENSITIVITY ANALYSIS
FOR SHP AND SFC FROM BASELINE SERIES 64

FIGURE 23 Sensitivity Analysis of Series 64 Hull Form

payload weight fraction. Neither case was examined for feasibility. They do demonstrate the extent of the impact of advanced technology applied to displacement ship design.

The comparison of DEH and the Series 64 hull form presented the cost of the foil system in terms of available payload for two ships of the same size. The Series 64 hull form designed to DEH standards has a greater payload carrying capacity than DEH. The 31 ton gain in payload capacity and greater endurance at low speeds for the Series 64 must again be traded-off against the superior performance of DEH in a seaway.

CHAPTER 4

CONCLUSIONS

The comparison of both a large and a small hydrofoil with a conventional ship designed for the same mission areas shows the benefits of applying advanced technology to ship design. In both cases the hydrofoil had superior payload carrying capability, a higher speed, and better sea state performance than the conventional ship as they were originally designed. However, the impact on a displacement ship of the hydrofoil's technology and design standards which permitted this apparent advantage is sizeable. A displacement hull form of similar size to the hydrofoil carries more payload and has the same speed and endurance as the hydrofoil at high speeds and a greater endurance at lower speeds when designed to hydrofoil standards. This indicates the cost of the inherently superior seakeeping characteristics of the hydrofoil. In terms of payload, the cost of the foil system is the loss of a 20 to 40 percent greater payload carrying capacity when compared with a displacement ship designed to hydrofoil standards. The choice then becomes one of cost, operational environment or projected mission in selecting the displacement form for its greater payload or the hydrofoil for its performance in a seaway.

The impact of hydrofoil design criteria on displacement ships shows the marked potential for improvement which is available from hydrofoil technology. The capabilities of a small, fast, displacement ship such as the Series 64 hull form designed to hydrofoil standards exceeds the capabilities of many of the larger surface combatants.

CHAPTER 5

RECOMMENDATIONS

The following areas are recommended for further study.

(1) The examination of other high performance vehicles (SES, SWATH, ACV) in the same manner to evaluate the potentials of the vehicles and the areas of design innovation.

(2) A detailed study of the feasibility of a small, 2000 ton or less, displacement ship for moderate speeds, 40 knots, using hydrofoil design criteria and standards.

(3) A cost estimate for the redesigned displacement ships to indicate the cost implications of the application of high performance design standards.

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APPENDIX A

SHIP DATA

Weights, volumes and other information used for the analysis of the ships in Section 3 are presented for reference in this section.

TABLE A-1

PG-84 WEIGHT AND VOLUME DATA

Weight Summary [18]

	Tons
GP1	66.6
GP2	46.9
GP3	8.7
GP4	8.0
GP5	20.6
GP6	24.2
GP7	13.2
Light Ship Displacement	188.2

Loads

Fuel	36.14
Ammo	8.25
Personnel (including stores)	6.89
Misc.	2.39
Full Load Displacement	241.87

Volume Summary

	Cubic Feet
Machinery Box Volume	13,320
Auxiliary Systems Volume	1,218
Access Volume	5,682
Payload Volume	7,093
Personnel Volume	11,961
Stores Volume	2,712
Fuel Volume	2,416
Total Volume	44,403

TABLE A-1 (continued)

Additional Data

Crew Size	24 (3 officers, 2 cpo's, 19 enlisted)
Total Installed Horsepower	14,750 HP
Installed KW of Generator Capacity	200 KW

TABLE A-2

PHM WEIGHT AND VOLUME DATA

Weight Summary [5]

	Tons
GP1	46.1
GP2	36.2
GP3	9.2
GP4	10.5
GP5	48.3
GP6	16.0
GP7	10.3
Light Ship Displacement	176.6

Loads

Fuel	41.3
Ammo	10.7
Personnel (including stores)	2.71
Full Load Displacement	231.3

Volume Summary

	Cubic Feet
Machinery Box Volume	12,550
Auxiliary Systems Volume	547
Access Volume	3,106
Payload Volume	8,066
Personnel Volume	8,069
Stores Volume	1,235
Fuel Volume	2,454
Foils	423
Total Volume	36,450

Additional Data

Crew Size	21 (5 officers, 4 cpo's, 12 enlisted)
Total Installed Horsepower	17,340 HP
Installed KW of Generator Capacity	400 KW

TABLE A-3

DEH WEIGHT AND VOLUME DATA

Weight Summary [21]

	Tons
GP1	205
GP2	68
GP3	42
GP4	83
GP5	256
GP6	51
GP7	31
Light Ship Displacement	736
Loads	
Fuel	407
Ammo	46
Personnel (including stores)	33
Full Load Displacement	1221

Volume Summary

	Cubic Feet
Machinery Box Volume	50,435
Auxiliary Systems Volume	930
Access Volume	1,860
Payload Volume	30,720
Personnel Volume	32,832
Stores Volume	697
Fuel Volume	16,809
Total Volume	154,040

Additional Data

Crew Size	82 (6 officers, 7 cpo's, 69 enlisted)
Total Installed Horsepower	
Installed KW of Generator Capacity	1200 KW

TABLE A-4

FFG-7 WEIGHT AND VOLUME DATA

Weight Summary [22]

	Tons
GP1	1320
GP2	275
GP3	166
GP4	97
GP5	409
GP6	283
GP7	104
Light Ship Displacement	2654
Loads	
Fuel	596
Ammo/Aircraft & Fuel	131
Personnel (including stores)	89
Misc.	26
Full Load Displacement	3496

Volume Summary

	Cubic Feet
Machinery Box Volume	57,912
Auxiliary Systems Volume	87,376
Access Volume	61,899
Payload Volume	97,800
Ship Control Volume	26,226
Personnel Volume	109,763
Stores Volume	10,471
Shop Volume	5,600
Fuel Volume	31,800
Tankage Volume	26,078
Total Volume	514,925

TABLE A-4
(continued)

<u>Additional Data</u>

Crew Size	185 (15 officers, 15 cpo's, 155 enlisted)
Total Installed Horsepower	40,000 SHP
Installed KW of Generator Capacity	3,000 KW

APPENDIX B

POWERING ESTIMATES FOR HULL FORMS USED IN THE ANALYSIS

B-1 230 Ton Planning Hull Power Estimate

For the comparative analysis of PHM and the redesigned PG-84 a powering estimate for a 230 ton hard-chine planning hull was required for an input to the computer model. The estimate was based on Series 62 data presented in Reference 23. The Series 62 was selected as the closest match to the PG-84 hull form. Model 4668 was selected for its low resistance at the speed and length required. The parameters for the hull form are tabulated below:

Δ = 230 ton

$L_p/B_{px} = 5.5$

Deadrise Angle = 12°

$L_p/\nabla^{\frac{1}{3}} = 7.5$

$LCG/L_p = 0.409$

L = 150 ft.

B_{px} = 27.27 ft.

R/Δ for $C_f = 0.004 = 0.1277$

$R_{BH} = R/\Delta \times \Delta = (0.1277)(230 \text{ tons})(2240 \text{ lb/ton})$

R_{BH} = 65,791 lb

Based on the data presented by Blount and Fox in Reference 24, an appendage resistance factor (η_A) of 0.913 was selected and a propulsive coefficient (η_D) of 0.6 was used.

$$R_T = R_{BH} + R_A$$

$$R_A = R_{BH}(1/\eta_A - 1) = 0.095\ R_{BH}$$

$$R_A = 6269 \text{ lb.}$$

$$R_T = 72{,}060 \text{ lb.}$$

$$EHP = \frac{R_T\ V}{550} = 9957 \text{ HP}$$

$$SHP = \frac{EHP}{\eta_D}$$

$$SHP = \frac{9957\text{HP}}{0.6} = 16{,}595 \text{ HP}$$

Based on this estimate, 17,000 shaft horsepower was used as the required shaft horsepower input to the model for a speed of 45 knots.

B-2 Powering Estimate for a 1200 Ton High Speed Displacement Ship

To provide a conceptual model to compare with DEH, a powering estimate for a 1200 ton, 45 knot displacement ship was made based on Series 64 (17). Series 64 is a round bottom hull form designed for high speed length ratios and as such was a logical choice for a small fast ship.

The hull form selected was a "conservative" Series 64 with the dimensions shown below. No attempt was made to optimize the hull form.

<u>1200 TON SERIES 64</u>

Displacement	1200 tons
Length	280 ft.
C_B	0.55
B/H	3.0
$V/\sqrt{L}$	2.7
S	8985 ft^2
$\frac{R_r}{\Delta}$	82.67
V	45 kts
$\frac{\Delta}{(0.01L)^3}$	55

From this data the total resistance and effective horsepower were computed.

$$Rt = 1/2\rho \quad S\nu^2 \ (C_f + \Delta C_f) + \frac{R_r}{\Delta} \ \Delta$$

$\rho = 1.99$

$S = 8985 \ ft^2$

$\nu = 76.05$ ft/sec

$C_f = 0.0014$

$\Delta C_f = 0.0004$

$$\frac{R_r}{\Delta} = 82.67 \text{ lb/ton}$$

$$\Delta = 1200 \text{ tons}$$

$$Rt_{BH} = 192{,}619 \text{ lb.}$$

$$R_T = Rt_{BH} + R_{APP}$$

Allowing a 10% allowance for appendage resistance,

$$R_T = 1.1\ Rt_{BH} = 211.881 \text{ lb.}$$

$$EHP = \frac{R_T\ V}{550} = 29{,}297 \text{ HP}$$

For an overall propulsive coefficient of 0.6 the required shaft horsepower for 45 knots is:

$$SHP = \frac{EHP}{\eta} = 48{,}820 \text{ HP}$$

Based on this estimate a required shaft horsepower of 50,000 SHP was used as an input for the computer model.

To determine the range at escort speeds (20 kts) an estimate was made for the same hull form at 20 kts.

$$V = 20 \text{ kts.}$$

$$\frac{V}{\sqrt{L}} = 1.20$$

$$B/H = 3.0$$

$S = 8985$ ft

$$\frac{R_r}{\Delta} = 24.87$$

$$Rt_{BH} = 1/2\rho\ S\nu^2(C_f + \Delta C_f) + \frac{R_r}{\Delta}\ \Delta$$

$$Rt_{BH} = 59{,}974 \text{ lb.}$$

$$Rt = Rt_{BH} + R_{APP}$$

Assuming 10 percent appendage allowance, $R_{APP} = 5997$ lb.

$$Rt = 65971 \text{ lb.}$$

$$EHP = \frac{Rt\nu}{550}$$

$$EHP = 4054$$

For a propulsive coefficient of $\eta = 0.60$

$$SHP = \frac{EHP}{\eta} = 6757 \text{ HP}$$

B-3 Powering Estimate for FFG-7 at High Speeds

To predict the maximum speed which would be possible using DEH design standards an estimate of the speed power relationship for FFG-7 at high speeds was required. Since the speeds involved were in excess of the Taylor Standard Series Values, the estimate was based on an extrapolation from the maximum known speed of 28 knots with a curve

proportional to the fourth power of the velocity. This curve was the basis for the shaft horsepower estimates for the FFG-7 at high speed and is shown in Figure B-1.

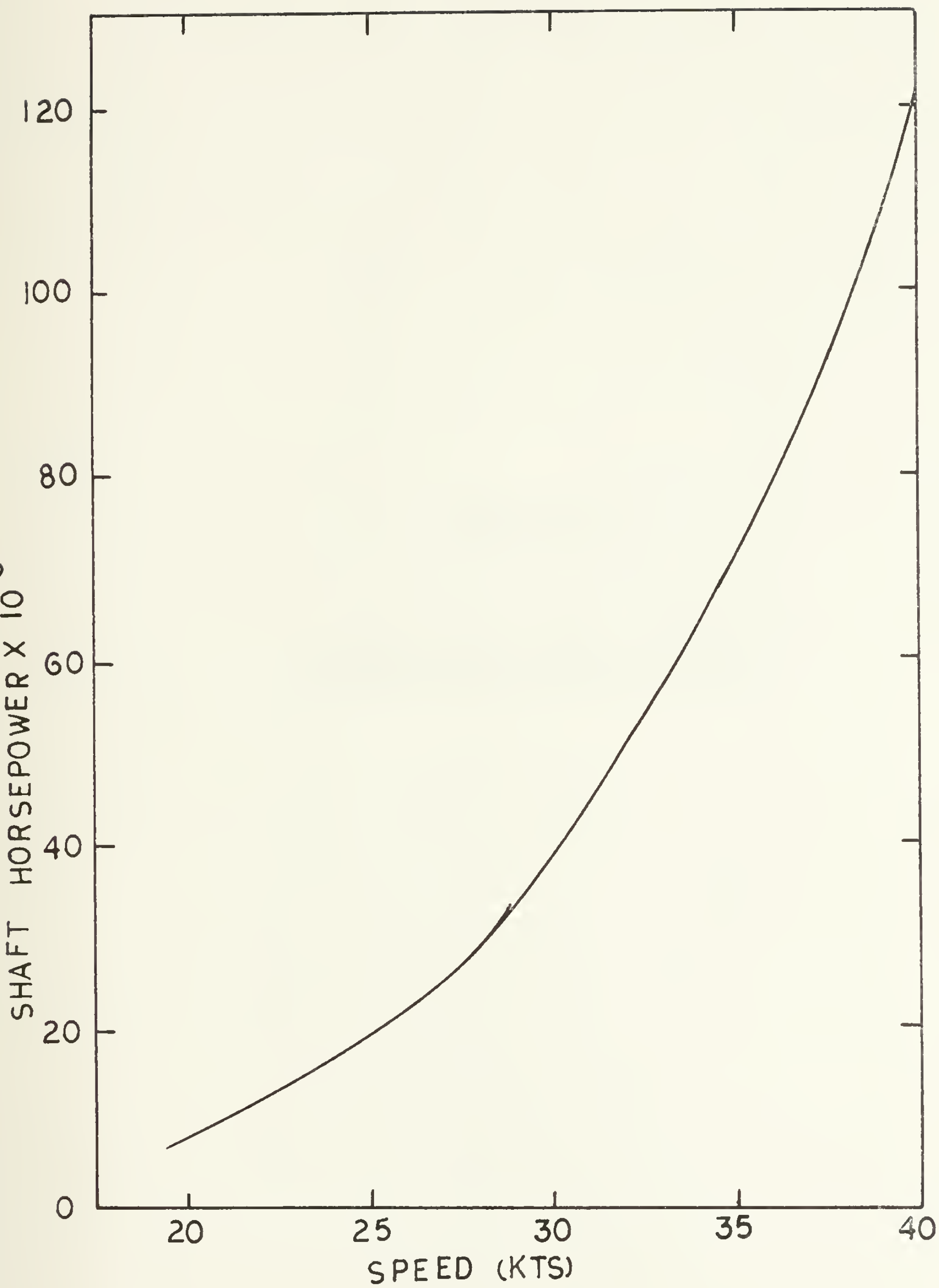

FIGURE B-1 FFG-7 Shaft Horsepower Estimate at High Speeds

APPENDIX C

COMPUTER PROGRAM LISTING

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C  DISPLACEMENT SHIP ANALYSIS PROGRAM  4/25/75
C
C
C  THE PURPOSE OF THIS PROGRAM IS TO TAKE A DISPLACEMETN HULL FORM OF A KNOWN
C  DISPLACEMENT AND HORSEPOWER REQUIREMENT FOR A GIVEN SPEED  AND ALLOW CHANGES
C  IN THE DESIGN CRITEREA AND STANDARDS AS REPRESENTED BY SPECIFIC PARAMETERS
C  SUCH AS STRUCTURAL DENSITY PROPULSION PLANT SPECIFIC WEIGHT, OR SPECIFIC
C  PERSONNEL VOLUME.
C
C INPUT DATA FORMAT
C  COLUMNS    FORMAT    VARIABLE
C   CARD NO 1
C   1-10       F10.2     DISPLACEMENT  (TONS)
C   11-20      F10.2     REQUIRED SHAFT HORSEPOWER AT SPECIFIED SPEED
C   21-30      F10.2     MAXIMUM SPEED
C   31-40      F10.2     RANGE AT MAXIMUM SPEED (NM)
C   41-50      F10.2     PROPULSION PLANT SFC (LB/SHP-HR)
C   51-60      F10.2     INSTALLED KW OF GENERATOR CAPACITY (KW)
C   61-70      F10.2     GENERATOR SFC (LB/SHP-HR)
C   71-75      F5.0      CREW SIZE (NO OF MEN)
C   76-80      F5.0      STORES ENDURANCE PERIOD  (DAYS)
C
C   CARD  2
C   1-10       F10.2     VEHICLE DENSITY (LB/CUFT)
C   11-20      F10.2     STRUCTURAL DENSITY (LB/CUFT)
C   21-30      F10.2     AUXILLARY SYSTEMS DENSITY (LB/CUFT)
C   31-40      F10.2     OTUFIT &FURNISHINGS DENSITY  (LB/CUFT)
C   41-50      F10.2     PROPULSION PLANT SPECIFIC WEIGHT  (LB/SHP)
C   51-60      F10.2     SHAFT HORSEPOWER MARGIN
C   61-70      F10.2     CREW WEIGHT  (LB/MAN  -  CREW AND EFFECTS)
C   71-80      F10.2     ELECTRICAL SYSTEM SPECIFIC DENSITY  (LB/KW)
C
C   CARD   3
C   1-10       F10.2     ASSUMED GENERATOR EFFICIENCY
C   11-20      F10.2     SPECIFIC MACHINERY VOLUME  (CUFT/SHP)
C   21-30      F10.2     FUEL DENSITY  (LB/CUFTE
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C    31-40      F10.2      SPECIFIC PERSONNEL VOLUME  (CUFT/MAN)
C    41-50      F10.2      TAILPIPE ALLOWNCE
C    51-60      F10.2      ARRANGEMENTS VOLUME FRACTION
C    61-70      F10.2      AUXILLARY SYSTEMS VOLUME FRACTION
C    71-80      F10.2      STORES VOLUME FRACTION
C
C    CARD  4
C    1-10       F10.2      STORES WEIGHT  (LB/MAN-DAY)
C    11-20      F10.2      REQUIRED PAYLOAD DENSITY  (LB/CUFT)
C
C   LAST CARD IN DATA SET REQUIRES 999. IN COLUMNS  1-10 TO END PROGRAM
C
C   PROGRAM LISTING
C
      REAL KW,KWWT
      I=0
    1 READ(8,100) DISPL, SHP, VMAX,RVMAX,SFC,KW,SFCA,CREW,SEND
      IF(DISPL.EQ.999.) GO TO 99
      READ(8,200) VDENS,SDENS,ADENS,FODENS,SHPDE,SHPMAR,CREWWT,KWWT
      READ(8,200) AUXEFF,SMACHV,FUELD,VPERS,TAILP,VFARR,VFAUX,VFS
      READ(8,300) STORWT,RPAY
C INPUT FORMAT CARDS
  100 FORMAT(7F10.2,2F5.0)
  200 FORMAT (8F10.2)
  300 FORMAT(2F10.2)
C DATA INPUT WRITE FORMAT CARDS
   10 WRITE(5,1300)
      WRITE(5,1400) DISPL, VMAX,RVMAX
      WRITE(5,1500) SHP, SHP, SFC
      WRITE(5,1800)KW,SFCA
      WRITE(5,1600)  CREW,SEND
      WRITE(5,2000)
      WRITE(5,2100) VDENS,SDENS
      WRITE(5,2200) ADENS,FODENS
      WRITE(5,2300) SHPDE,SHPMAR
      WRITE(5,2400) CREWWT,KWWT
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      WRITE(5,2500) AUXEFF,SMACHV
      WRITE(5,2600) FUELD,VPERS
      WRITE(5,2700) TAILP,VFAUX,VFS,VFARR
      WRITE(5,2800) STORWT,RPAY
 1300 FORMAT('1',5X,'DESIGN AND PERFORMANCE REQUIREMENTS')
 1400 FORMAT('0',5X,'DISPLACEMENT FULL LOAD',2X,F6.1,2X,'TONS',5X,'MAX
     1SPEED',2X,F6.1,2X,'KNOTS',5X,'RANGE AT MAX SPEED',6X,F6.1,2X,'NM')
 1500 FORMAT('0',5X,'SHP AT VMAX',12X,F7.0,2X,'HP',7X,'SFC AT',F8.0,2X,'
     1SHP',5X,F7.2,2X,'LB/SHP-HR')
 1600 FORMAT('0',5X,'CREW',18X,F6.0,3X,'MEN',4X,'STORES ENDURANCE',8X,F6
     1.0,3X,'DAYS')
 1800 FORMAT('0',5X,'ELECTRICAL LOAD',7X,F8.1,2X,'KW',5X,'GENERATOR SFC'
     1,2X,F6.3,'LB/HP-HR')
 2000 FORMAT('0',5X,'INPUT PARAMETERS')
 2100 FORMAT('0',5X,'VOLUMETRIC DENSITY',2X,F6.2,2X,'LB/CUFT',5X,'STRUCT
     1URAL DENSITY',2X,F6.2,2X,'LB/CUFT')
 2200 FORMAT('0',5X,'AUX DENSITY',2X,F6.2,2X,'LB/CUFT',5X,'OUTFIT&FURNIS
     1HING DENSITY',2X,F6.2,'LB/CUFT')
 2300 FORMAT('0',5X,'PROPULSION PLANT DENSITY',2X,F6.2,'LB/SHP',5X,'SHP
     1MARGIN',2X,F6.3)
 2400 FORMAT('0',5X,'SPECIFIC PERSONNEL WT',2X,F6.2,2X,'LB/MAN',5X,'SPEC
     1IFIC ELECTRIC PLANT DENSITY',2X,F6.2,2X,'LB/KW')
 2500 FORMAT('0',5X,'ELECTRIC PLANT EFF',2X,F6.2,5X,'SPECIFIC MACH VOL',
     12X,F6.2,2X,'CUFT/SHP')
 2600 FORMAT('0',5X,'FUEL DENSITY',2X,F6.2,2X,'LB/CUFT',5X,'SPECIFIC PER
     1SONEL VOL',2X,F6.2,2X,'CUFT/MAN')
 2700 FORMAT('0',5X,'TAIL PIPE ALLOW',2X,F6.3,5X,'AUX VOL FRACTION',2X,F
     16.3,5X,'STORES VOLUME FRACTION',2X,F6.3,//,6X,'ARRANGEMENT VOL FRA
     2CTION',2X,F6.2)
 2800 FORMAT('0',5X,'STORES WT',2X,F6.2,2X,'LB/MAN-DAY',5X,'REQUIRED PAY
     1LOAD DENSITY',2X,F6.2,'LB/CUFT')
C WEIGHT SYNTHESIS
      N=0
    2 IF(N.GT.50) GO TO 6
      VOL=(DISPL/VDENS)*2240.
      GP1=VOL*SDENS/2240.
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      GP3=KW*KWWT/2240.
      GP5=VOL*ADENS/2240.
      GP6=VOL*FODENS/2240.
      SHPR=SHP*SHPMAR
      GP2=SHP*SHPDE/2240.
      PERS=CREW*CREWWT/2240.
      STORES=CREW*SEND*STORWT/2240.
      FF=EXP((RVMAX*SFC*SHPR)/(DISPL*VMAX*2240.))
      FWTP=(FF*DISPL-DISPL)/FF
      FWTA=1.34*SFCA*KW*RVMAX/(VMAX*AUXEFF*2240.)
      FUELWT=(FWTP+FWTA)/TAILP
      PAY=DISPL-GP1-GP2-GP3-GP5-GP6-FUELWT-STORES-PERS
      IF (PAY.LE.0.0) GO TO 5
C WEIGHT FRACTIONS
      FGP1=GP1/DISPL
      FGP2=GP2/DISPL
      FGP3=GP3/DISPL
      FGP5=GP5/DISPL
      FGP6=GP6/DISPL
      FFUEL=FUELWT/DISPL
      FPERS=PERS/DISPL
      FSTORE=STORES/DISPL
      FPAY=PAY/DISPL
C VOLUME SYNTHESIS
      VMACH=SHPR*SMACHV
      VFUEL=(FUELWT/FUELD)*2240.
      VCREW=CREW*VPERS
      VARR=VOL*VFARR
      VAUX=VOL*VFAUX
      VSTORE=VOL*VFS
      VPAY=VOL-VMACH-VFUEL-VCREW-VARR-VAUX-VSTORE
      DPAY=(PAY/VPAY)*2240.
      IF(DPAY.LT.RPAY) GO TO 3
      VDENS=VDENS-0.1
      N=N+1
      GO TO 2
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    3 IF (DPAY.GT.RPAY-1.) GO TO 4
      VDENS=VDENS+0.1
      N=N+1
      GO TO 2
    4 VFM=VMACH/VOL
      VFF=VFUEL/VOL
      VFC=VCREW/VOL
      VFP=VPAY/VOL
C OUTPUT WRITE STATEMENTS
      WRITE(5,1000)
      WRITE(5,2001)
      WRITE(5,3000) GP1, FGP1
      WRITE(5,4000) GP2,FGP2,VMACH,VFM
      WRITE(5,5000)GP3,FGP3
      WRITE(5,6000)GP5,FGP5,VAUX,VFAUX
      WRITE(5,7000) GP6,FGP6,VARR,VFARR
      WRITE(5,8000)PAY,FPAY,VPAY,VFP
      WRITE(5,9000) PERS,FPERS,VCREW,VFC
      WRITE(5,1100) STORES, FSTORE,VSTORE,VFS
      WRITE(5,1200) FUELWT,FFUEL,VFUEL,VFF
      WRITE(5,1201) DISPL, VOL
      WRITE (5,1202) VDENS,DPAY
C OUTPUT FORMT CARDS
 1000 FORMAT('0',17X,'WEIGHT',7X,'WEIGHT',25X,'VOLUME',7X,'VOLUME')
 2001 FORMAT(' ',17X,'(TONS)',6X,'FRACTION',23X,'(CUBIC FT)',5X,'FRACTIO
     1N')
 3000 FORMAT('0',5X,'GROUP 1',3X,F10.2,3X,F10.3)
 4000 FORMAT('0',5X,'GROUP 2',3X,F10.2,3X,F10.3,5X,'MACHINERY VOL',3X,F1
     10.2,3X,F10.3)
 5000 FORMAT('0',5X,'GROUP 3',3X,F10.2,3X,F10.3)
 6000 FORMAT('0',5X,'GROUP 5',3X,F10.2,3X,F10.3,5X,'AUXILLARY VOL',3X,F1
     10.2,3X,F10.3)
 7000 FORMAT('0',5X,'GROUP 6',3X,F10.2,3X,F10.3,5X,'ACCESS VOL   ',3X,F1
     10.2,3X,F10.3)
 8000 FORMAT('0',5X,'PAYLOAD',3X,F10.2,3X,F10.3,5X,'PAYLOAD VOL  ',3X,F1
     10.2,3X,F10.3)
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9000 FORMAT('0',5X,'PERSN L',3X,F10.2,3X,F10.3,5X,'PERSONEL VOL ',3X,F1
    10.2,3X,F10.3)
1100 FORMAT('0',5X,'STORES ',3X,F10.2,3X,F10.3,5X,'STORES VOL    ',3X,F1
    10.2,3X,F10.3)
1200 FORMAT('0',5X,'FUEL    ',3X,F10.2,3X,F10.3,5X,'FUEL VOL      ',3X,F1
    10.2,3X,F10.3)
1201 FORMAT('0',5X,'DISPL  ',3X,F10.2,18X,'TOTAL VOLUME',3X,F10.2)
1202 FORMAT('0',5X,'VOLUMETRIC DENSITY',5X,F10.1,10X,'PAYLOAD DENSITY',
    15X,F10.3)
     GO TO 1
   5 WRITE (5,1111)
1111 FORMAT('0',5X,'PAYLOAD LESS THAN ZERO')
     WRITE(5,3000) GP1, FGP1
     WRITE(5,4000) GP2,FGP2,VMACH,VFM
     WRITE(5,5000)GP3,FGP3
     WRITE(5,6000)GP5,FGP5,VAUX,VFAUX
     WRITE(5,7000) GP6,FGP6,VARR,VFARR
     WRITE(5,8000)PAY,FPAY,VPAY,VFP
     WRITE(5,9000) PERS,FPERS,VCREW,VFC
     WRITE(5,1100) STORES, FSTORE,VSTORE,VFS
     WRITE(5,1200) FUELWT,FFUEL,VFUEL,VFF
     WRITE(5,1201) DISPL, VOL
     WRITE (5,1202) VDENS,DPAY
     GO TO 1
   6 WRITE(5,1115)
1115 FORMAT('0',5X,'VOLUME NOT FEASIBLE')
     WRITE(5,3000) GP1, FGP1
     WRITE(5,4000) GP2,FGP2,VMACH,VFM
     WRITE(5,5000)GP3,FGP3
     WRITE(5,6000)GP5,FGP5,VAUX,VFAUX
     WRITE(5,7000) GP6,FGP6,VARR,VFARR
     WRITE(5,8000)PAY,FPAY,VPAY,VFP
     WRITE(5,9000) PERS,FPERS,VCREW,VFC
     WRITE(5,1100) STORES, FSTORE,VSTORE,VFS
     WRITE(5,1200) FUELWT,FFUEL,VFUEL,VFF
     WRITE(5,1201) DISPL, VOL
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      WRITE (5,1202) VDENS,DPAY
      GO TO 1
   99 CONTINUE
      STOP
      END
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Thesis 103948
G8607 Grostick
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